AFC-02-303-PNNL

AAA Interim Status Report for the Period January 1, 2001 - December 31, 2001

TITLE:
Interim Status Report for Tensile Tests Conducted Between January 1, 2000 and December 31, 2001

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1. Scope

This report presents the tensile data obtained at Pacific Northwest National Laboratory (PNNL) during the period from January 1, 2000 to December 31, 2001. During this period tensile tests were performed on 304L stainless steel (SS), 316L SS, Mod 9Cr-1Mo steel, Alloy 718, and Al 6061. A few tests were performed at room temperature, 50°C, 164°C, 300°C, 400°C, 500°C, and 600°C. The materials were either in an unirradiated (control test) condition or were irradiated with a mix of mainly protons and some spallation neutrons. As the incident particles were mainly protons, "proton irradiation" will be stated when referring to this irradiation environment. During proton irradiation, specimen temperatures were somewhere between 35°C to 120°C. The specimens tested at 300°C, 400°C, 500°C, and 600°C were held at the target test temperature for one (1) hour prior to performing the tensile test. The data included in this report are the 0.2% offset-strain yield strength (YS), the ultimate tensile strength (UTS), the engineering uniform elongation (EUE), and the total elongation (TE). Also included are the stress-strain traces from which the tensile properties were obtained.

These tests were done to satisfy the requirements of Test Specification-Proton and Neutron Irradiation Effects on Tensile Properties for APT Target/Blanket Assembly Metallic Structural Materials, APT-MP-98-08, APT-102-1998-58. Rev. 3, July 2000. This requirement calls for quantifying the effects of the APT proton and neutron irradiation environment on the tensile properties of candidate structural materials for the APT target/blanket assembly.

2. Applicable Documents

All testing was performed according to the requirements specified in the Test Plan for Determining Proton and Neutron Irradiation Effects on Tensile Properties at PNNL for APT Target/Blanket Assembly Metallic Structural Materials (APT-MP-98-24, Rev. 0, December 1999) and the TPO Test Specification (APT-MP-98-08, Rev. 0, May 1998). Tests were conducted according to PNNL procedure 1122-T1 Rev. 2 and calibrations of test equipment were performed in accordance with APT-TPO-QMPP, Rev. 0 as referenced in the Test Plan, APT-MP-98-24, Rev. 0, December 1999.

3. Requirements

3.1 Materials

The materials tested were 304L SS, 316L SS, Mod 9Cr-1Mo, Alloy 718, and Al 6061-T4. The 304L SS and 316L SS were in an annealed condition prior to irradiation, the Mod 9Cr-1Mo was in a normalized and tempered condition prior to irradiation, Alloy 718 was in a precipitation hardened condition, and the Al 6061 was in a T4 condition. Details on the heat treatments and specifications for these materials can be found in the Implementation Procedure Describing the Preparation of Specimens for Irradiation, APT-MP-96-01, Rev. 0, TPO-E72-Z-PRO-X-00012, Rev. 0, July 1996.

3.2 Test Method

Tensile testing was performed in an Instron 1122 load frame located in the 323 building hot cell at PNNL. Specimen gauge dimensions were measured prior to each test. Specimens were interfaced with the test frame using clamp-grip type grips. When mounting the specimen in the grips, axial alignment of the grip and specimen assembly was ensured by applying a slight load (5 pounds) to the grips and then fixing the position of the grips prior to clamping down a specimen. The preload process also allows a specimen to bottom out on the alignment pins which minimizes the possibility that a specimen will slip in the grips during a test. The preload was removed after clamping. All tensile tests at temperatures above 200°C were performed in flowing argon. Load and displacement were measured every 0.1 second. Merlin, which is a software package from Instron, was used for test control and data acquisition. Back-up copies of data files were stored on a zip disk immediately after each test. Additional back-up copies were later stored on a PNNL server and on the Principal Investigator's computer.

Heat-up was performed with a constant one-pound load maintained on the specimen which is less than 15 MPa for the thinnest specimen. For the specimens tensile tested at 300°C, 400°C (only the unirradiated specimens), 500°C, and 600°C, the length of time that specimens were above 90% of the test temperature (in Kelvin) prior to the onset of tensile testing was generally about 2 hours. All other specimens tested at elevated temperature were above 90% of the test temperature for about 1-1.5 hours prior to the start of a tensile test. The extended hold-times were performed because examination of identically irradiated TEM specimens held at elevated temperature for the same period of time is planned. The data do not provide any methods for evaluating the effect of the additional hold-time.

Specimen temperature, load cell output, and crosshead speed and displacement were calibrated according to the test plan prior to the start of each test. All tests were performed at a displacement rate of 0.005 in./min., corresponding to an initial strain rate of 4×10^{-4} sec^{-1}. All tests were performed using a 1000-pound load cell that was accurate to within 2 pounds. Dimensional measurements on the specimens were made using a calibrated digital micrometer located in the hot cell and were accurate to 0.0002 inches. Specimen temperatures were maintained to within ±5°C. Mechanical properties obtained from the test traces included 0.2% offset yield strength (YS), ultimate tensile strength (UTS), engineering uniform elongation (EUE) and total elongation (TE). YS was determined by finding the intersection between the test trace and a straight line drawn parallel to the elastic loading portion of the trace but offset by 0.2% strain. UTS was determined at the point of maximum load. EUE was taken to be the plastic strain at the point of maximum load (onset of necking). TE was determined as the plastic strain at failure. For most tests, the strength and elongation values were determined automatically by Merlin after a user specifies the load range in the elastic region which is fit to a straight line.

The tensile traces obtained for all tests reported here are given in **Appendix 1**. Each of the figures shown in the appendix includes 3 traces and a straight line fit to the elastic portion of the raw trace. The original raw test trace is referred to as 'data' in the legend. The straight line fit to the initial elastic deformation is referred to as 'regression line' in the legend. Two compensations were made to convert the original test trace to a trace representative of the actual material behavior. It was assumed that the compliance evident in the test trace represented the combined compliance of the specimen and the testing machine. The strain associated with this compliance was removed by subtracting the strain associated with the regression line at the same load (below the load range over which the line was fit, the trace was simply zeroed out); this is referred to in the legend as the 'compliance compensated' curve. The elastic compliance of the specimen was added back to each trace using the known Young's modulus of the material; this is referred to as the 'modulus compensated' line in the legend.

While automated analysis of the tensile curves was performed by the Merlin software, several of the traces contained test-system-induced anomalies that would cause Merlin to report erroneous tensile properties. Generally, these anomalies were thought to be caused by minor slippage of a specimen in the grips and were manifested as sharp but relatively small load drops during a test. In these instances, the tensile properties were manually obtained from the tensile traces. The erroneous tensile properties obtained from Merlin during such tests were within a few percent the manually obtained tensile properties.

3.3 Test Matrix

The test matrix consists of specimens tested between January 1, 2000 and December 31, 2001 and is shown in **Table 1**. Tensile test temperatures ranged from room temperature up to 600°C while doses ranged from 0.2 to 9 dpa. Specimens to be tested at either 300°C, 400°C (unirradiated only), 500°C, or 600°C were held at the target tensile test temperature for 1 hour prior to testing. For the other tests, specimens were tested within 15 minutes of reaching the target test temperature.

4. Results

This section focuses on the quality of the raw test data. Interpretation of the results is left for the discussion section. The raw data, presented as engineering stress versus engineering strain tensile traces, can be found in **Appendix 1**.

4.1 304L SS

Only one 304L SS tensile test was performed (2-7-6). The test was performed at room temperature. The raw tensile trace shows that after typical non-linear behavior at low loads, the trace becomes linear up to the point of microyielding. There is no evidence of slippage or other anomalous behavior in the test trace.

4.2 316L SS

Tensile tests were performed at either room temperature, 50°C, 164°C, or 300°C. The one tensile test which was performed at room temperature (4-7-6) shows no unusual behavior. Tensile traces from the 50°C tests show non-linear loading behavior in the low load elastic deformation region but eventually transition to linear loading before yielding. The one test performed at 164°C (4-7-5) and the controls tested at 300°C (316-14 and 316-15) also display some non-linear loading in the tensile trace at low loads, but these traces also eventually transition to linear behavior. Saw-tooth like edges are apparent at the high plastic strains in the unirradiated controls which are suggestive of the specimen slipping in the grips. The irradiated specimens tested at 300°C (24-6-3 and 24-6-4) are generally well behaved with one minor exception; Specimen 24-6-4 displays some sharp but small load drops just prior to the onset of linear loading which are probably due to slippage of the specimen in the grips.

4.3 Mod 9Cr-1Mo

The traces for all the controls (9Cr-9 through 9Cr-13) display anomalous behavior prior to the onset of plastic deformation. There are unusual fluctuations in the slope of the loading line, and slippage, manifested as load drops during elastic loading, is evident in all the controls. The traces for the irradiated Mod 9Cr-1Mo show the same type of behavior.

4.4 Alloy 718

Specimen 1-5-5 is well behaved, but like the other materials discussed, the 1-5-6 trace shows some non-linear loading behavior in the elastic deformation regime. In particular, the elastic loading line never quite becomes linear before reaching yield.

4.5 Al 6061-T4

The 0.2 dpa specimens showed no unusual tensile behavior, however there is evidence of specimen slippage in the grips, manifested as load drops, during the tensile tests of the 1.3 dpa specimens.

4.6 Comments on the Non-Standard Tensile Behavior

In most instances, it was possible to account for the non-linear loading and the load drops when measuring the tensile properties. The exceptions are the 316L SS controls tested at 300°C and 1-5-6 (Alloy 718). The saw tooth shape of the unirradiated 316L SS test traces during plastic deformation indicates slippage. The slippage results in the observed elongation being larger than the actual elongation. The difference between observed and actual elongation is likely less than a few percent strain which is only a small fraction of the measured strain. For the Alloy 718 test (1-5-6), since the trace never became linear prior to yield, it was difficult to measure the yield point. By applying different line fits to the loading line, it appears that the error between measured and actual yield is probably no greater than ±3% of the measured yield strength.

5. Discussion

Specimens generally came in thicknesses of either 10 mils (0.25 mm) or 30 mils (0.75 mm). The appearance of the tensile traces and the mechanical properties obtained from 10 mil and 30 mil thick specimens were often slightly different (which may have resulted from the fact that the 10 mil and 30 mil thick specimens were, with the exception of the Mod 9Cr-1Mo, obtained from two different heats of material), such as shown in **Fig. 1**, and as a result the new data here are compared only to other data obtained from specimens of the same thickness. In the comparative plots which are referenced in this section, new data are indicated by ***bold-italic*** specimen IDs in the plot legends. The mechanical properties obtained from the newly tested specimens are listed in **Table 2**.

5.1 304L SS

Only a single specimen was tested (2-7-6). This specimen was irradiated at 90°C to a dose of 7 dpa and was tensile tested at room temperature. Other 0.75 mm 304L SS specimens which could be used for comparison were irradiated at lower temperature, to lower doses, and were tensile tested at higher temperatures. Thus, comparing the mechanical properties from 2-7-6 to the mechanical properties from the other 0.75 mm thick specimens presents a challenge because there are no common experimental variables. As can be seen in **Fig. 2**, the most obvious difference between the 2-7-6 trace and the other 304 SS traces is that 2-7-6 has a much higher yield stress. Contributing factors to this differing behavior could be that 1) 2-7-6 was irradiated at 90°C whereas the other specimens were irradiated at temperatures between 33°C and 75°C, 2) 2-7-6 was irradiated to 7 dpa versus 3.9 dpa for the next highest dose specimens, and 3) 2-7-6 was tensile tested at room temperature and the other specimens were tensile tested at 50°C or higher. There is insufficient information in the 304SS traces to determine which variable is causing the greatly increased yield stress, but the answer can be found by examining the 316L SS traces. **Fig. 3** shows that two 316L SS specimens were irradiated at 120°C to between 8 and 9 dpa. One specimen (4-7-6) was tensile tested at room temperature while the other (4-7-5) was tensile tested at 164°C. As with the 304 SS tests, the specimen tensile tested at room temperature displays a much higher yield stress which suggests that tensile testing 304 SS (and 316L SS) at room temperature can result in a yield strength much greater than what would be observed if the tensile test was performed at a slightly elevated temperature.

5.2 316L SS

Table 1 shows which specimens were tensile tested between January 1, 2000 and December 31, 2001. Consider first specimens 4-7-6 and 4-7-5 which were irradiated at 120°C to 8.7 dpa and 8.3 dpa and tensile tested at 22°C and 164°C, respectively and are shown in **Fig. 3** along with unirradiated specimens also tensile tested at either 22°C or 164°C. Consider first that there is a large change in the tensile properties of the unirradiated material when the tensile test temperature changes from 22°C to 164°C. Yield strength drops by nearly 30%, and EUE drops by about 50%. This behavior is suggests that dislocation pinning and multiplication processes are reduced over the 22°C to 164°C temperature range. Relative to this change in behavior of the unirradiated material, it should not be so surprising that for the irradiated material, YS drops by 17%, and EUE drops to less than 1%. The drastic drop in EUE can be understood in that when the irradiated material was tensile tested at 22°C, the rate of work hardening was essentially zero, and thus if there is any reduction in work hardening ability due to a temperature increase, this would cause the uniform elongation to drop to near zero.

Next, consider the two control specimens (316-14 and 316-15) and two irradiated 316L SS specimens (24-6-3 and 24-6-4) which were irradiated to 2.5 dpa and then tensile tested at 300°C. The traces for these tests are shown in **Fig. 4**. The effect of radiation is to significantly increase the yield and ultimate strength while reducing the uniform elongation. However, the irradiated material still displays acceptable uniform elongation and good work hardening behavior at this dose and tensile test temperature.

Now consider the two 316L SS specimens which were tensile tested at 50°C after approximately 2.5 dpa of irradiation (4-5-5 and 4-5-6). In **Fig. 5a**, the traces from these two tests are compared to traces obtained from other 316L SS specimens tensile tested at 50°C. The general behavior of 4-5-5 and 4-5-6 are similar to two sets of specimens irradiated to 2.8 and 3.0 dpa, respectively. Irradiation temperatures were within 10°C. Common features are visible yield points and zero work hardening. However, 4-5-5 and 4-5-6 have approximately 15% higher yield stresses and reduced total elongation compared to the two sets of specimens which were irradiated to higher dose. The increased yield strength may be due to the slightly higher irradiation temperature of 4-5-5 and 4-5-6 which was 54°C compared to 48°C (2.8 dpa) and 44°C (3.0 dpa), but such a small difference in irradiation temperature seems unlikely to make a difference even at these relatively low temperatures. It is also possible that the differing behavior is due to the irradiation spectrum. Specimens 4-5-5 and 4-5-6 were irradiated in the direct proton beam achieving their final dose of 2.5 dpa in two months, whereas 4-6-3, 4-6-4, 24-5-7, and 24-5-8 were irradiated in the beam periphery achieving their final dose in six months. This results in a factor of 3 difference in dose rate. And as a result being placed in the beam periphery, 4-6-3, 4-6-4, 24-5-7, and 24-5-8 received less He and H. With the current data, it is difficult to determine if the difference in mechanical properties is due more to dose rate effects on mechanical properties or the added gas accumulation, but it is known that bubble formation resulting from accumulation of He in austenitic steels will cause an increase in yield strength. The increase in yield strength depends on the amount of He that accumulates.

As an aside, the traces in **Fig. 5a** may provide some clues to the conditions required to cause loss of uniform elongation after irradiation. For these engineering stress versus engineering strain traces, there appears to be a maximum engineering UTS that can be achieved at a particular test temperature, and when the yield strength of the material exceeds this maximum engineering UTS, loss of uniform elongation occurs. This idea seems to work well when considering the irradiated material engineering stress and strain traces, but the engineering UTS of the unirradiated controls is far below the engineering UTS of the irradiated materials. Now, if traces are compared using true stress and true strain up to necking which has been performed by Byun, et al. for other materials **[1]**, the story changes somewhat as shown in **Fig. 5b**. The unirradiated and irradiated true UTS values all approximately match, and it can be seen that those specimens which necked upon yielding have a yield stress which approximately matches the observed true UTS. Byun, et al., observed a similar trend.

5.3 Mod 9Cr-1Mo

Tensile tests were performed at either 400°C, 500°C, or 600°C. Test traces of the unirradiated specimens are shown as thin lines in **Fig. 6**, while the irradiated specimens are shown as thick lines. The tensile behavior of the irradiated material is similar to the unirradiated with the exception that the irradiated material has greater strength. **Fig. 7** shows the tensile behavior of the unirradiated material for tensile test temperatures ranging from 20°C to 600°C. Examination of the unirradiated material tensile property trends as a function of temperature in **Fig. 8** show that YS, UTS, and EUE all decrease with increasing tensile test temperature which is typical for similar materials **[2]**. TE decreases until about 400°C and then steadily rises up to 600°C. **Fig. 9** shows the tensile behavior of Mod 9Cr-1Mo irradiated to between 1 dpa and 3 dpa when tensile tested at temperatures ranging from 20°C to 600°C. Shown in **Fig. 10** are the corresponding tensile properties. Low temperature irradiation to doses between 1-3 dpa increases the YS and UTS relative to the unirradiated material at all the tensile test temperatures. However, the effect of irradiation had a varied effect on EUE and TE. At tensile test temperatures below 400°C, it appears that the EUE is decreased by low temperature irradiation whereas at tensile test temperatures between 400°C and 600°C, the EUE of the irradiated material is either greater than or equal to the unirradiated values. TE shows a similar trend. The increase in the YS and UTS is easily explained by the creation of extended defects during irradiation, however there are several possible reasons for the higher EUE and TE in the irradiated material. One possible reason is that the increased extended defect density increases the dislocation multiplication rate which then allows the material to strain harden more effectively. Another possible reason is that heating to temperatures between 400°C and 600°C causes changes in the microstructure that result in improved work hardening behavior and increased uniform elongation. As the pre-irradiation microstructure is relatively insensitive to temperatures less than 600°C for such short periods of time, it seems likely that the irradiation induced microstructure would be evolving when aged for short times at these temperatures. **Fig. 11** shows the tensile behavior of Mod 9Cr-1Mo after 9 dpa when tensile tested at either 164°C or 500°C. The tensile properties from these tests are shown in **Fig. 12**. Compared to the 1-3 dpa tensile properties, at 9 dpa, the YS and UTS are increased while the EUE and TE are decreased.

5.4 Alloy 718

Two tensile tests were performed at 50°C on specimens irradiated at 53°C to about 2.7 dpa. The traces from these tests are compared to traces for the other Alloy 718 specimens tested at 50°C in **Fig. 13**. The new tests represent the highest dose tested at this tensile test temperature. The data suggest that the effect of irradiation on the tensile properties of Alloy 718 is nearly constant for doses between 0.4 dpa and 2.7 dpa. The only clear trend in the data is a decrease in total elongation with increasing dose. In all instances, the effect of irradiation relative to the unirradiated controls is to increase the yield strength, eliminate nearly all strain hardening capacity, and significantly reduce both the uniform and total elongation. These observations are reflected in **Fig. 14** which shows the mechanical properties of Alloy 718 at 50°C plotted as a function of dose.

5.5 Al 6061-T4

Two specimens with a doses of about 0.2 dpa and two specimens with doses of about 1.3 dpa were tensile tested at 50°C. The traces from these tests are plotted in **Fig. 15** with the other 6061-T4 specimens tensile tested at 50°C. The new data extends the minimum and maximum doses for tests performed at 50°C. With the exception of the 0.65 dpa specimens (29-6-4 and 29-6-5) and the 0.75 dpa specimens (29-6-17 and 29-6-18), the 50°C traces show that the effect of increasing dose is to increase the yield strength and UTS while decreasing the uniform and total elongations. While the uniform and total elongations decrease with dose, the new data show that after 1.3 dpa at approximately 40°C, the reductions are not drastic with 6061-T4 maintaining good elongation characteristics. These observations are reflected in **Fig. 16** which shows the mechanical properties of Al 6061-T4 at 50°C plotted as a function of dose.

6. Conclusions

Tensile tests were successfully performed on a variety of unirradiated and irradiated materials. The mechanical properties obtained from these tests have provided further insight into the behavior of APT candidate materials. The observations can summarized as follows:

- *304L SS:* A single tensile test was performed at room temperature. After 7 dpa of proton irradiation at 90°C, this material has a large amount of uniform elongation but the engineering UTS is approximately equal to the YS when tensile tested at room temperature.

- *316L SS:* Several specimens of varying dose were tensile tested at a variety of temperatures. A room temperature tensile test was performed on a specimen proton irradiated to about 8.7 dpa at 120°C. This specimen had deformation characteristics very similar to the 7 dpa 304L SS specimen tensile tested at room temperature. A tensile test was performed at 164°C on a specimen irradiated to 8.3 dpa at 120°C. This specimen had an approximately 20% lower yield strength and showed no evidence of uniform elongation. Both unirradiated and irradiated specimens were tensile tested at 300°C. After about 2.5 dpa of proton irradiation at about 50°C, 316L SS maintains work hardening capability when tensile tested at 300°C. Relative to the unirradiated material, the yield strength is increased while the uniform elongation is decreased. Two irradiated 316L SS specimens were tensile tested at 50°C. The traces were compared to other traces from tensile tests performed at 50°C on other irradiated 316L SS specimens. The mechanical properties from the new tests are in general agreement with other specimens of similar dose. The resulting trends in the traces suggest that at any particular test temperature both unirradiated and irradiated specimens have the same approximate true UTS, and when the yield strength reaches or exceeds this true UTS, nearly complete loss of uniform elongation occurs.

- *Mod 9Cr-1Mo:* Tensile tests were performed at 400°C, 500°C, and 600°C on unirradiated and irradiated Mod 9Cr-1Mo. The effect of test temperature on the unirradiated material is to decrease yield strength, ultimate strength, and uniform elongation. The effect of test temperature on the materials irradiated at approximately 50°C is to decrease yield and ultimate stress but increase uniform and total elongation for test temperatures between 250°C and 500°C. The uniform and total elongation of Mod 9Cr-1Mo tensile tested at 400°C, 500°C, and 600°C after about 2 dpa of proton irradiation are actually greater than or equal to the unirradiated values. At about 9 dpa, the uniform and total elongation at 400°C are about the same as the unirradiated material, but at 500°C, the uniform elongation is still higher in the irradiated material. The data suggest that holding these specimens at 400-600°C causes thermal aging of the irradiated microstructure which leads to the improved tensile properties of the irradiated material.

- *Alloy 718:* Two tensile tests were performed at 50°C on specimens irradiated to about 2.7 dpa. The tensile properties from these tests combined with previous tensile tests show that the tensile properties of Alloy 718 at 50°C are relatively insensitive to dose for doses between 0.4 dpa and 2.7 dpa.

- *Al 6061-T4:* Two sets of two tensile tests were performed each at 50°C on specimens irradiated to 0.2 dpa and 1.3 dpa. These tests extend the upper and lower dose boundaries of the measured tensile properties of this material. This data combined with previous data show that the effect of irradiation to doses between 0.2 dpa and 1.3 dpa is to steadily increase the yield and ultimate strength while steadily decreasing the total elongation. The uniform elongation initially decreases but then shows no change between 0.6 and 1.3 dpa. While the uniform and total elongation of irradiated Al 6061-T4 are decreased relative to the unirradiated condition, after 1.3 dpa Al 6061-T4 maintains good tensile properties.

7. Recommendations for Future Work

Microstructural observations on the 316L SS tensile tested at 300°C and the Mod 9Cr-1Mo tensile tested at 400°C and 500°C are recommended and are in progress. Tensile tests performed at 300°C on 316L SS after about 4 dpa would be useful in exploring the loss of work hardening capability that these materials exhibit.

8. References

[1] T.S. Byun, K. Farrell, E.H. Lee, J.D. Hunn, and L.K. Mansur, “Strain hardening and plastic instability properties of austenitic steels after proton and neutron irradiation”, to be published in the Journal of Nuclear Materials.

[2] Bae, et al, Journal of Nuclear Materials, Vols. 191-194, 1992, pp. 905-909.

Table 1 -- Tensile specimens tested between January 1, 2000 and December 31, 2001.

Alloy	ID	thickness (mils)	dose (dpa)	T_{irr} (°C)	T_{test} (°C)
304L SS	2-7-6	30	7	90	22
316L SS	4-7-5	30	8.3	120	164
	4-7-6	30	8.7	120	22
	4-5-5	10	2.6	54	50
	4-5-6	10	2.4	54	50
	316-14†	30	---	---	300
	316-15†	30	---	---	300
	24-6-3	30	2.5	52	300
	24-6-4	30	2.6	52	300
Mod 9Cr-1Mo	9Cr-9†	10	---	---	400
	9Cr-10†	10	---	---	400
	9Cr-11†	10	---	---	500
	9Cr-12†	10	---	---	500
	9Cr-13†	10	---	---	600
	23-5-5	10	2.2	34	500
	23-5-6	10	2.0	34	500
	4-3-5	10	8.7	65	500
	4-3-6	10	9.1	65	500
	23-5-9	10	2.0	35	600
Alloy 718	1-5-5	10	2.8	53	50
	1-5-6	10	2.7	53	50
Al 6061	1-5-7	10	1.3	43	50
	1-5-8	10	1.3	43	50
	1-5-11	10	0.2	32	50
	1-5-12	10	0.2	32	50

† Unirradiated control specimens

Table 2 -- Engineering tensile properties for specimens tested between January 1, 2000 and December 31, 2001.

Alloy	ID	Yield Stress (MPa)	UTS (MPa)	Uniform Elongation (%)	Total Elongation (%)
304L SS	2-7-6	929	981	18.5	21.2
316L SS	4-7-5	733	767	0.6	16.6
	4-7-6	879	930	16.6	23.4
	4-5-5	823	831	0.4	17.4
	4-5-6	822	853	0.6	13.9
	316-14†	204	456	34.9	50.9
	316-15†	220	458	29.9	44.6
	24-6-3	552	595	12.8	25.8
	24-6-4	571	591	12.1	25.5
Mod 9Cr-1Mo	9Cr-9†	613	692	2.6	9.9
	9Cr-10†	603	671	2.5	8.8
	9Cr-11†	555	598	1.9	10.3
	9Cr-12†	540	568	1.3	9.9
	9Cr-13†	426	438	0.7	14.8
	23-5-5	660	720	4.1	13.1
	23-5-6	639	708	3.3	11.6
	4-3-5	752	800	2.0	7.8
	4-3-6	750	825	3.2	9.1
	23-5-9	530	547	1.2	13.4
Alloy 718	1-5-5	1190	1289	1.8	8.6
	1-5-6	1278	1302	0.9	7.6
Al 6061	1-5-7	203	267	9.7	12.0
	1-5-8	191	255	10.0	12.9
	1-5-11	157	224	14.0	19.6
	1-5-12	173	251	14.9	18.6

† Unirradiated control specimens

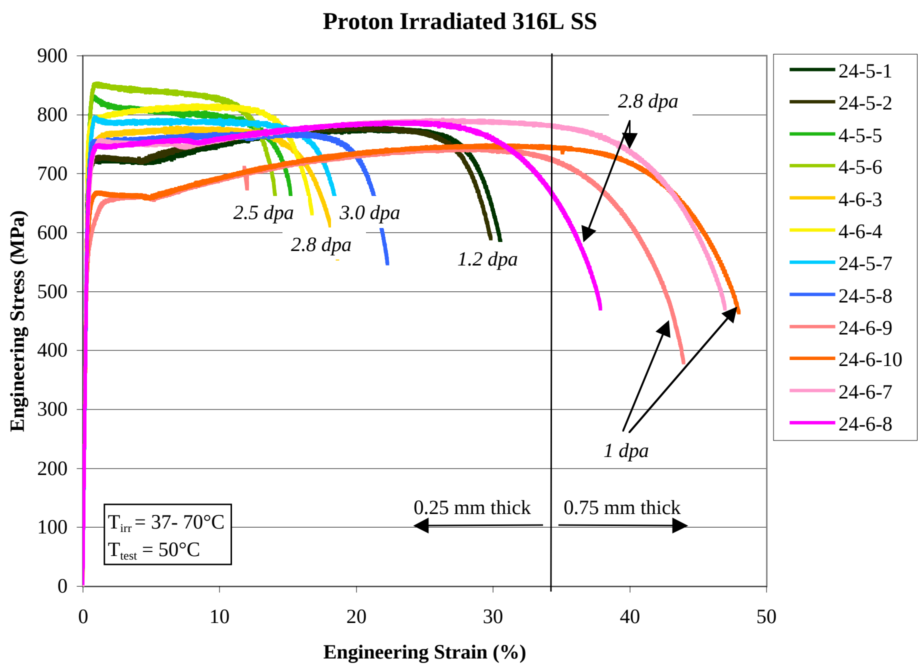

Figure 1 -- 316L SS tensile traces showing the difference in trace behavior between 10 mil and 30 mil thick irradiated specimens.

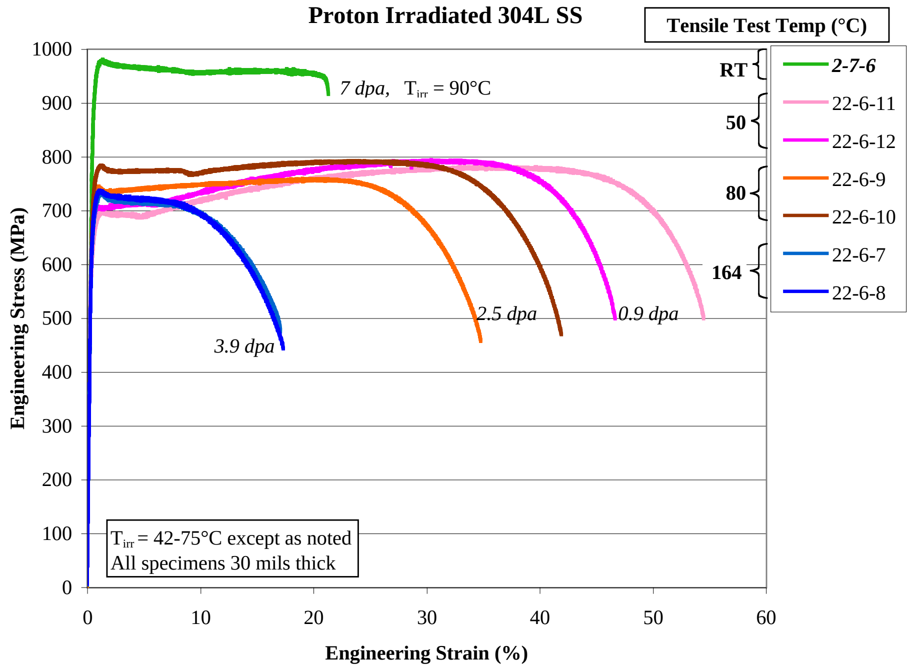

Figure 2 -- Engineering stress versus engineering strain tensile traces of proton irradiated 304L SS after irradiation to various doses and testing at temperatures ranging from room temperature to 164°C.

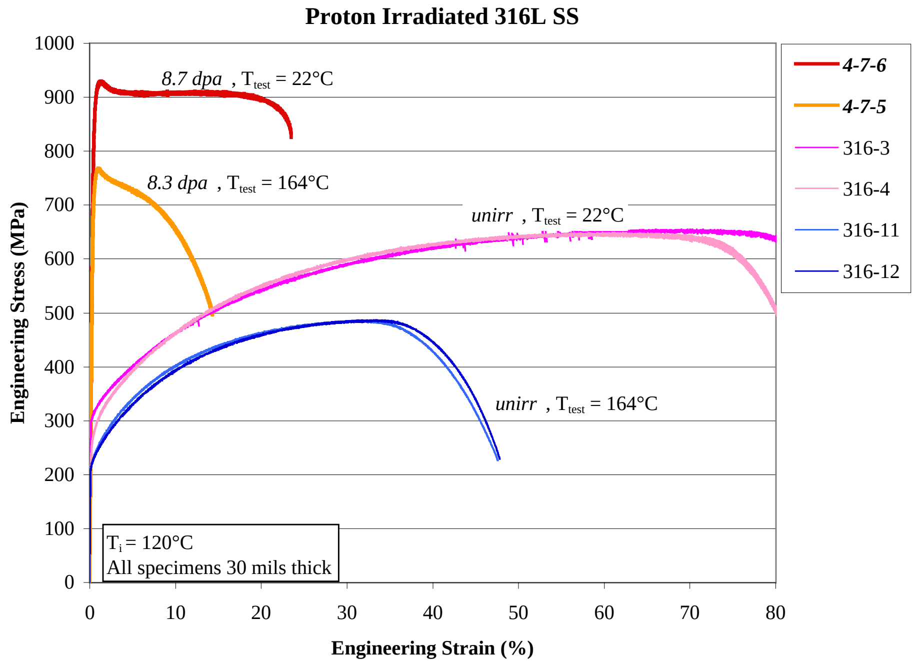

Figure 3 -- Engineering stress versus engineering strain tensile traces of unirradiated and proton irradiated 316L SS tensile tested at either room temperature or 164°C.

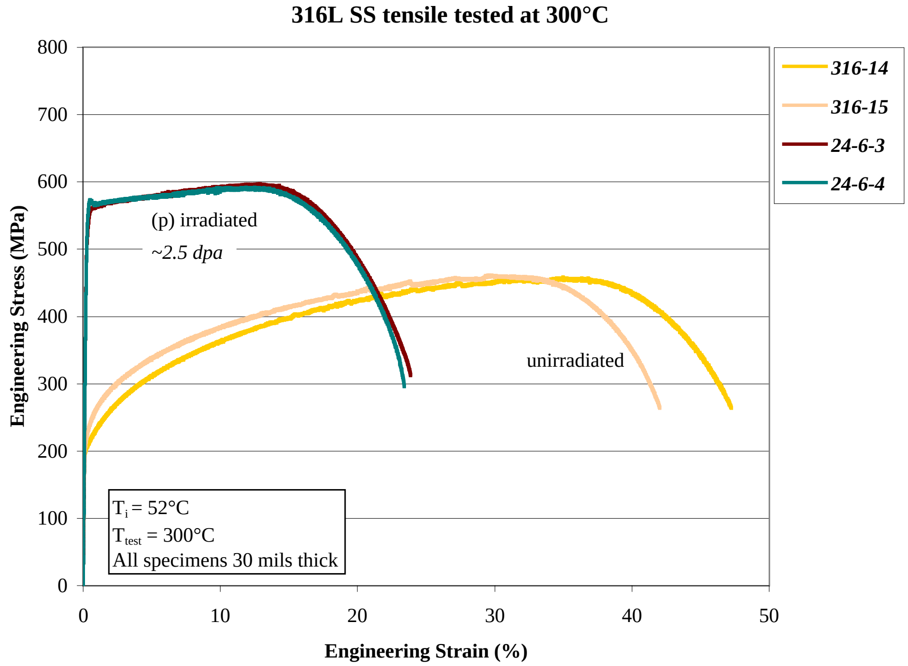

Figure 4 -- Engineering stress versus engineering strain tensile traces of 316L SS tensile tested at 300°C.

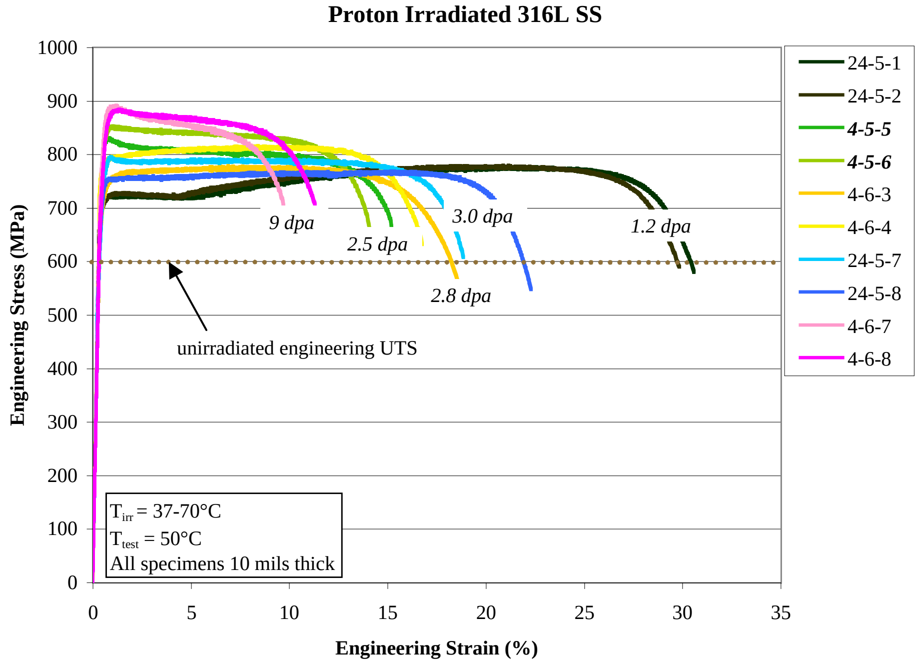

Figure 5a -- Engineering stress versus engineering strain traces of proton irradiated 316L SS tensile tested at 50°C. Green dotted line indicates the engineering UTS of the unirradiated material at 50°C.

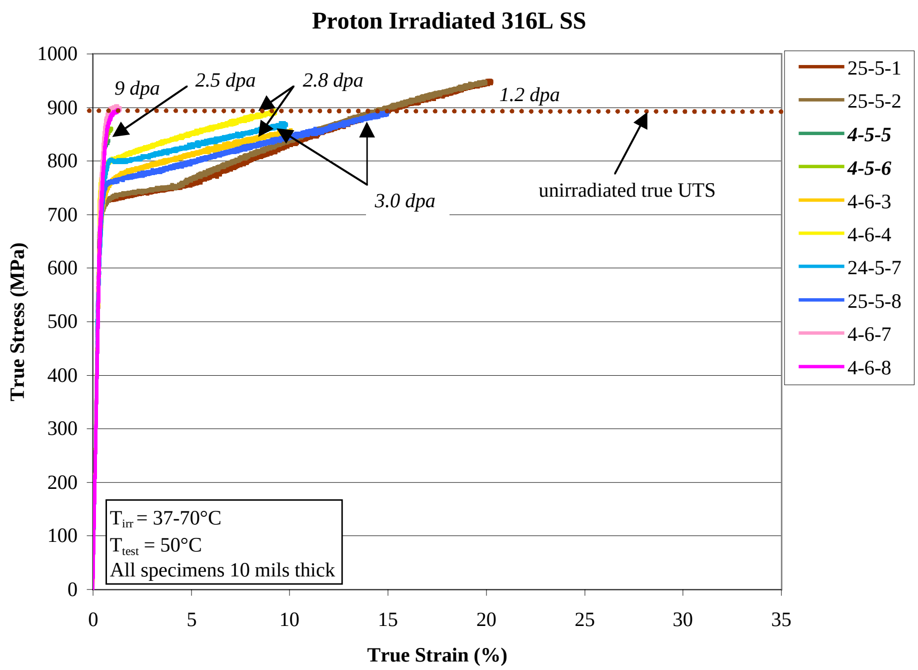

Figure 5b -- True stress versus true strain traces to the point of necking for proton irradiated 316L SS tensile tested at 50°C. Green dotted line indicates the true UTS of the unirradiated material at 50°C.

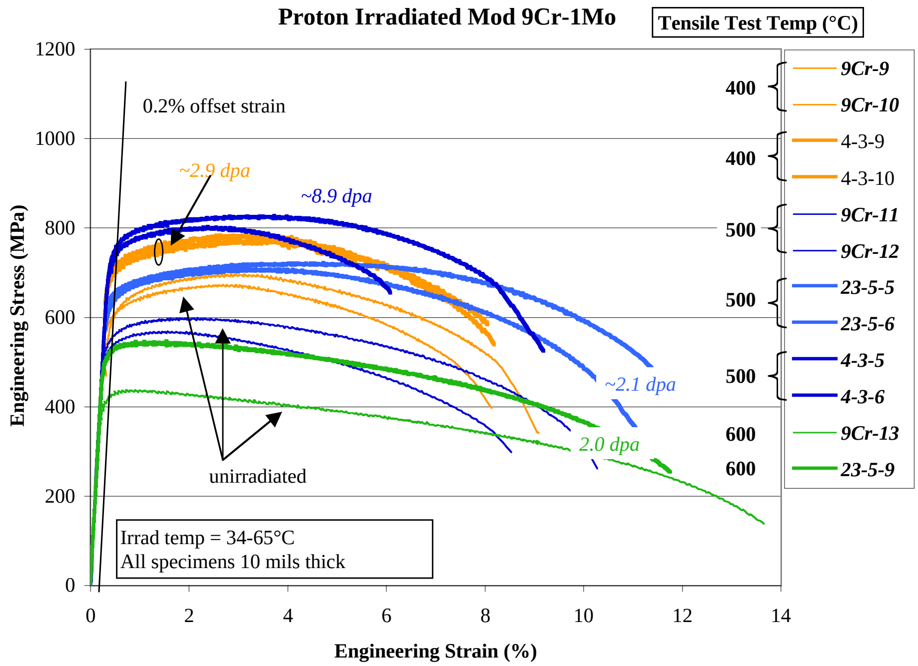

Figure 6 -- Engineering stress versus engineering strain traces of Mod 9Cr-1Mo tensile tested at 400°C, 500°C, and 600°C.

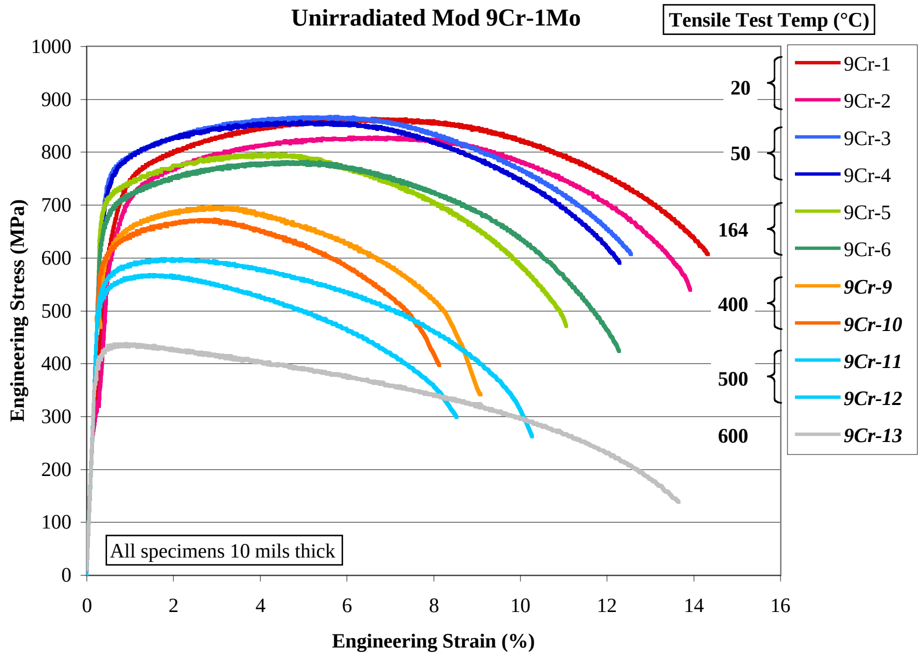

Figure 7 -- Engineering stress versus engineering strain traces of unirradiated Mod 9Cr-1Mo tensile tested at temperatures ranging from 20°C to 600°C.

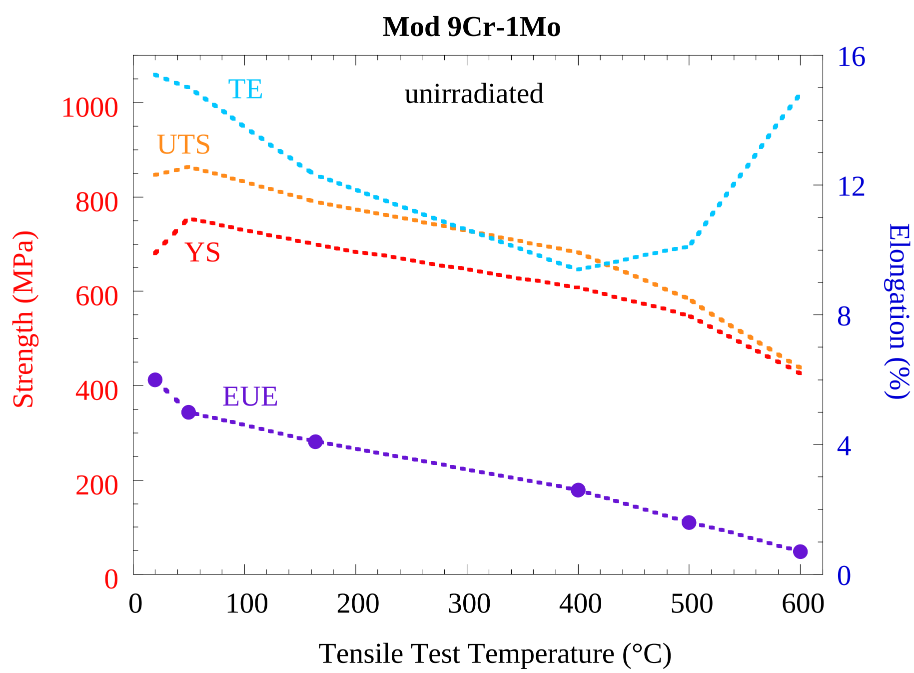

Figure 8 -- Tensile properties of unirradiated Mod 9Cr-1Mo as a function of tensile test temperature.

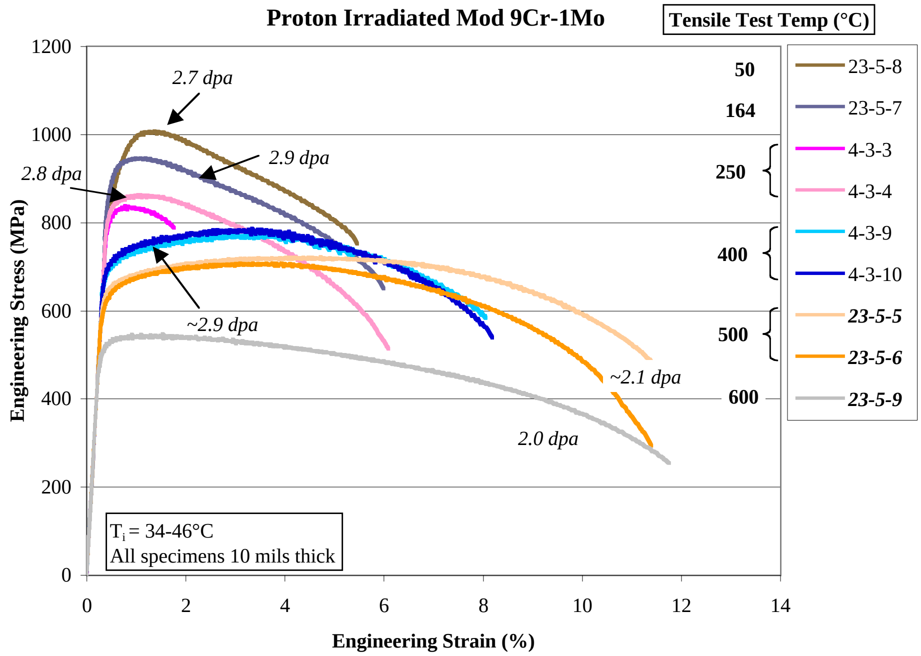

Figure 9 -- Engineering stress versus engineering strain traces of Mod 9Cr-1Mo irradiated to doses between 2 and 3 dpa and tensile tested at temperatures between 50°C and 600°C.

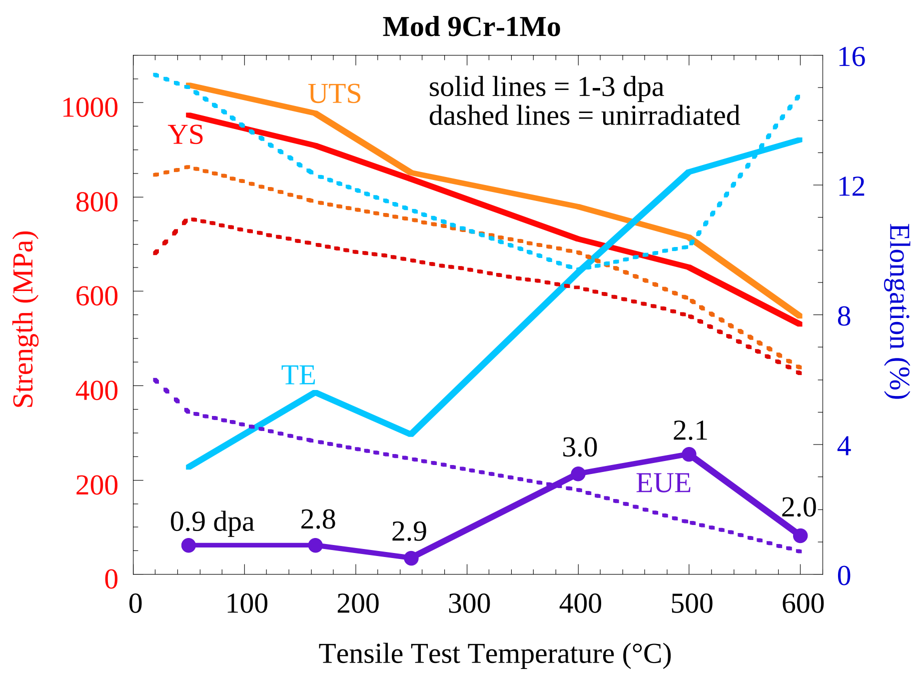

Figure 10 -- Tensile properties of Mod 9Cr-1Mo plotted as a function of tensile test temperature for unirradiated material and material irradiated to doses from 1-3 dpa. Irradiation temperature varied from 34-46°C.

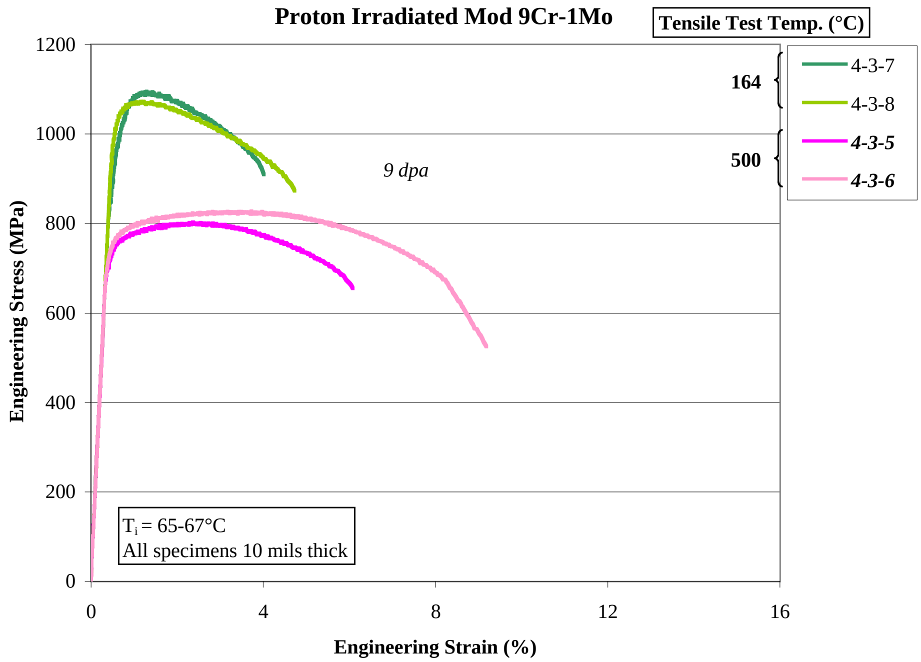

Figure 11 -- Engineering stress versus engineering strain traces of Mod 9Cr-1Mo irradiated to a dose of about 9 dpa and tensile tested at either 164°C or 500°C.

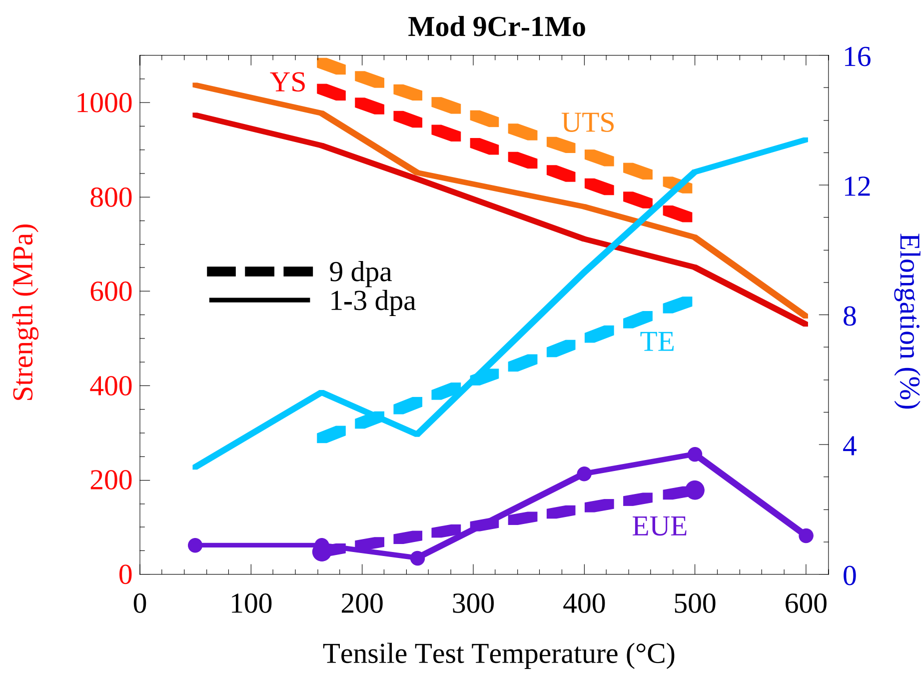

Figure 12 -- Tensile properties of Mod 9Cr-1Mo plotted as a function of tensile test temperature for material irradiated to 1-3 dpa or about 9 dpa. Irradiation temperature of 9 dpa material was between 65 and 67°C.

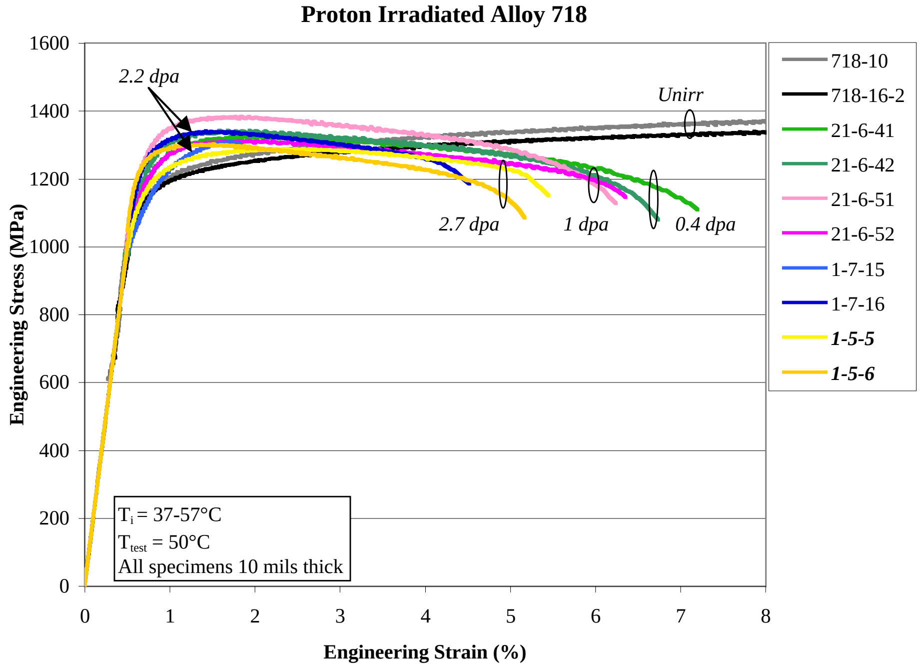

Figure 13 -- Engineering stress versus engineering strain traces of Alloy 718 tensile tested at 50°C.

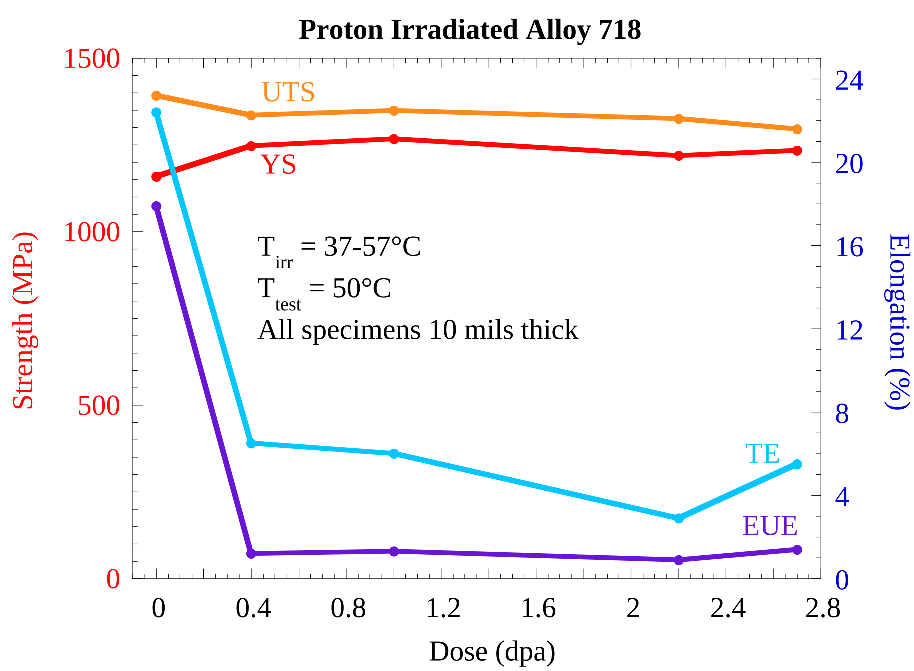

Figure 14 -- Tensile properties of irradiated Alloy 718 plotted as a function of dose for material tensile tested at 50°C.

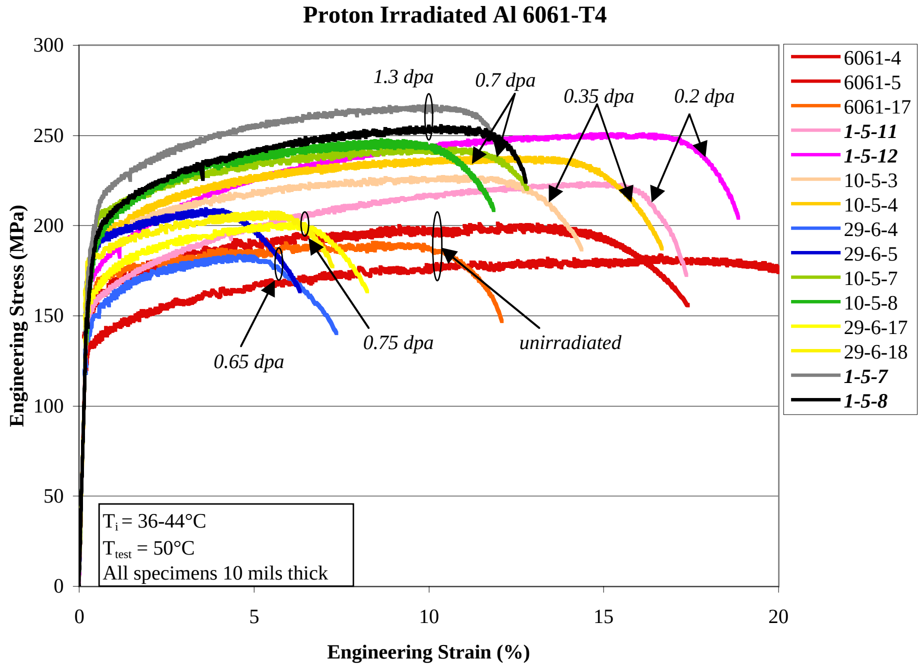

Figure 15 -- Engineering stress versus engineering strain traces of Al 6061-T4 tensile tested at 50°C.

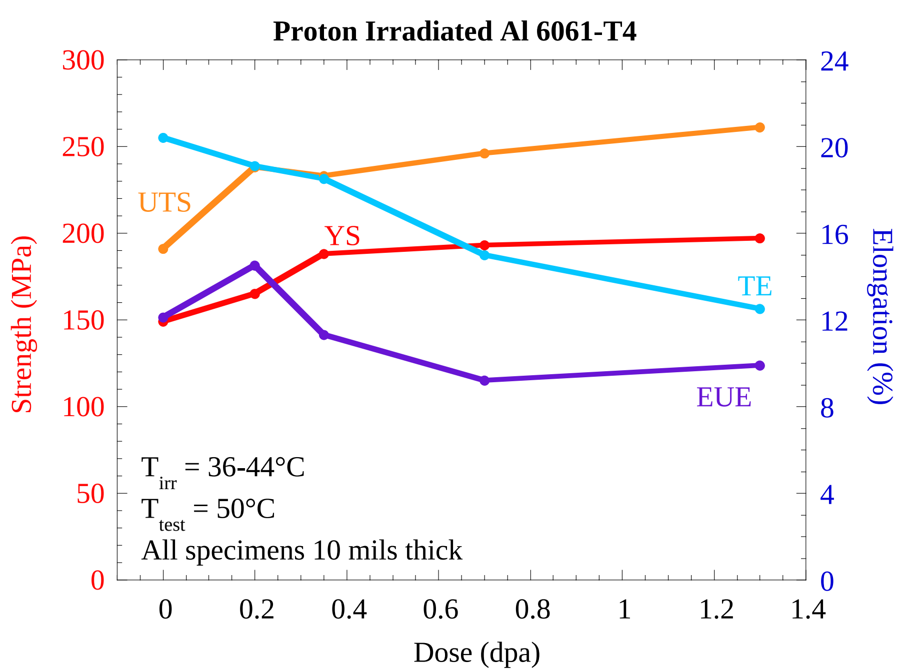

Figure 16 -- Tensile properties of irradiated Al 6061-T4 plotted as a function of dose for material tensile tested at 50°C.

Appendix 1: Raw tensile traces (engineering stress versus engineering strain)

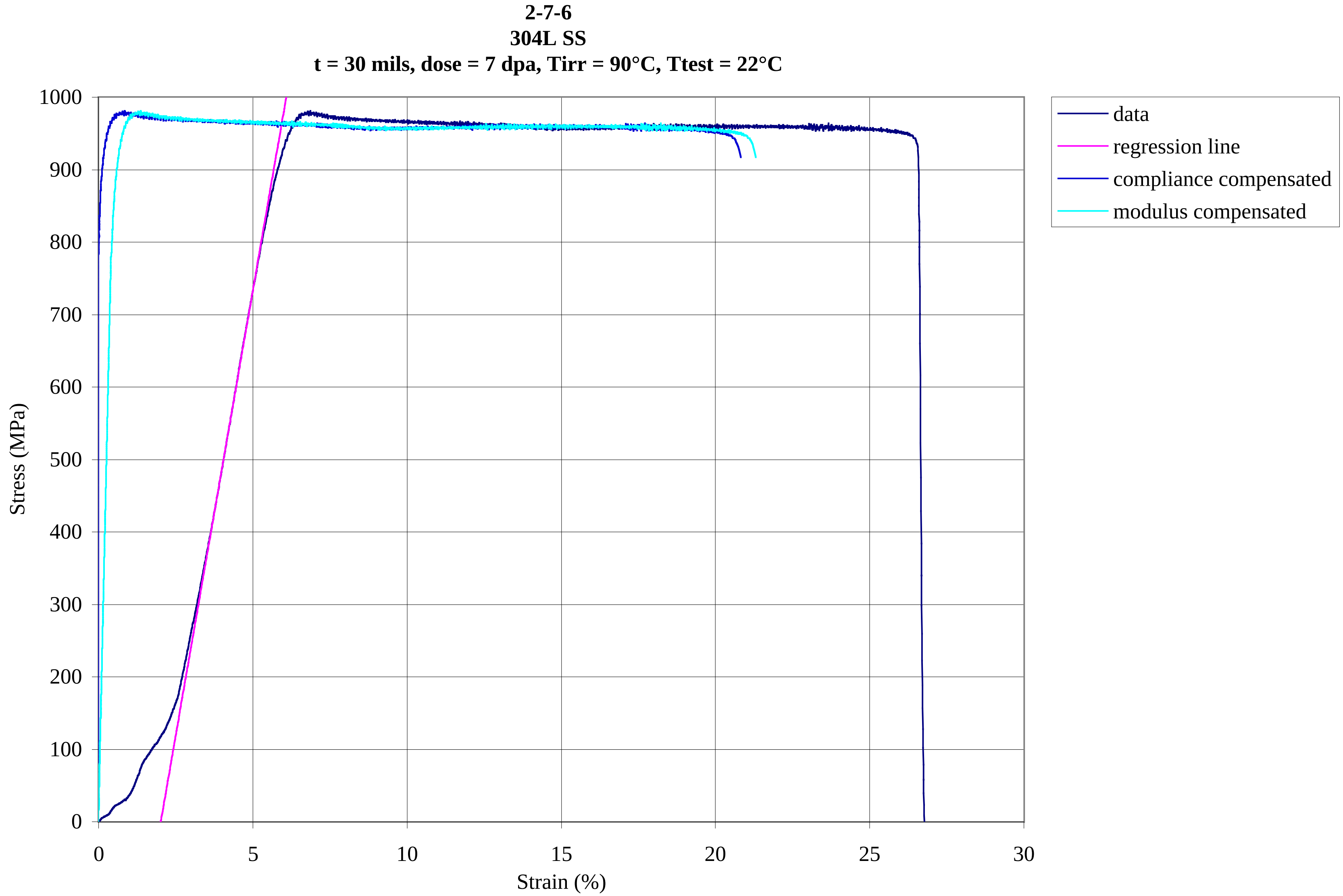

Figure A1-1 -- Tensile traces for specimen 2-7-6 (304L SS).

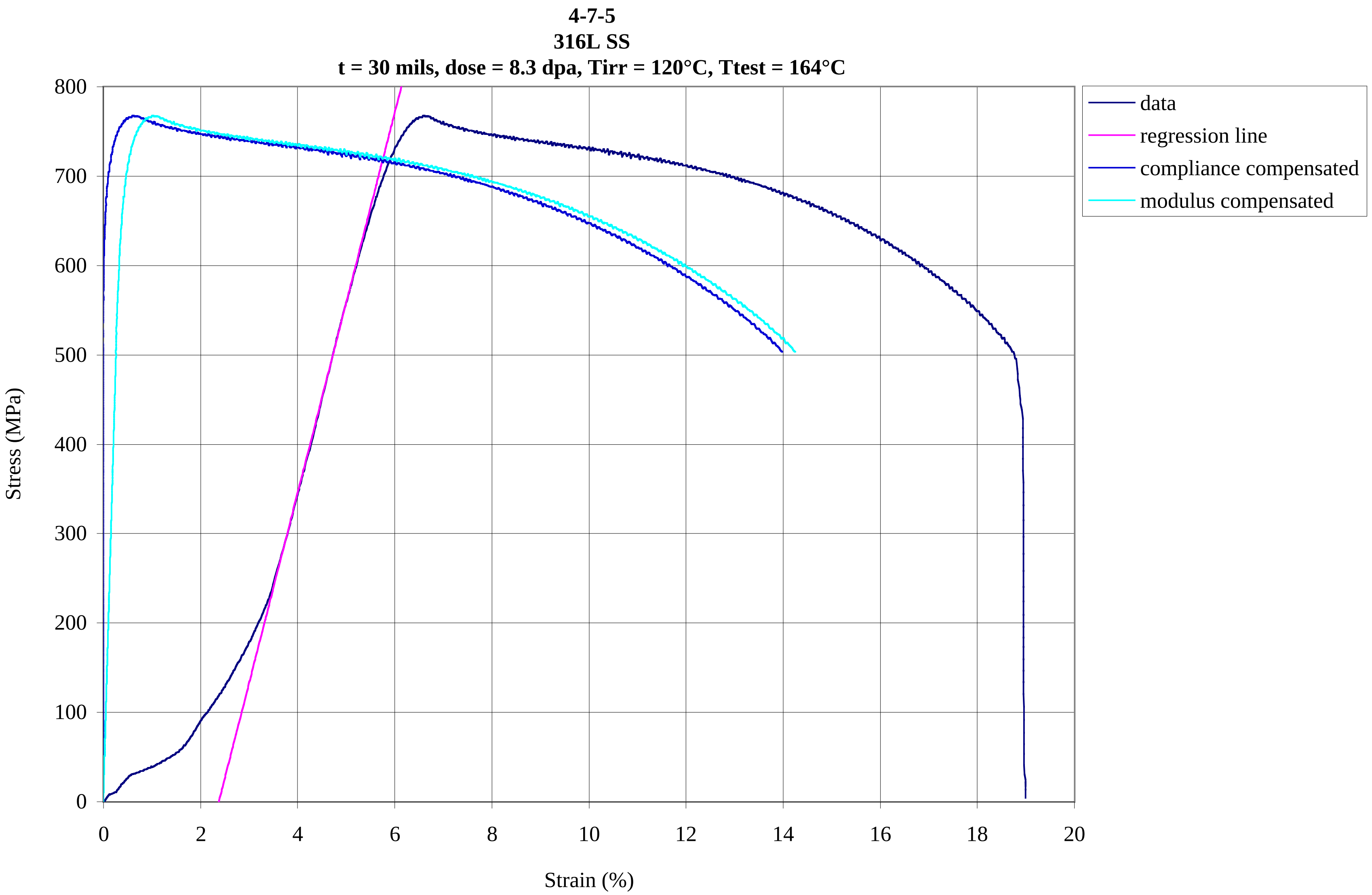

Figure A1-2 -- Tensile traces for specimen 4-7-5 (316L SS).

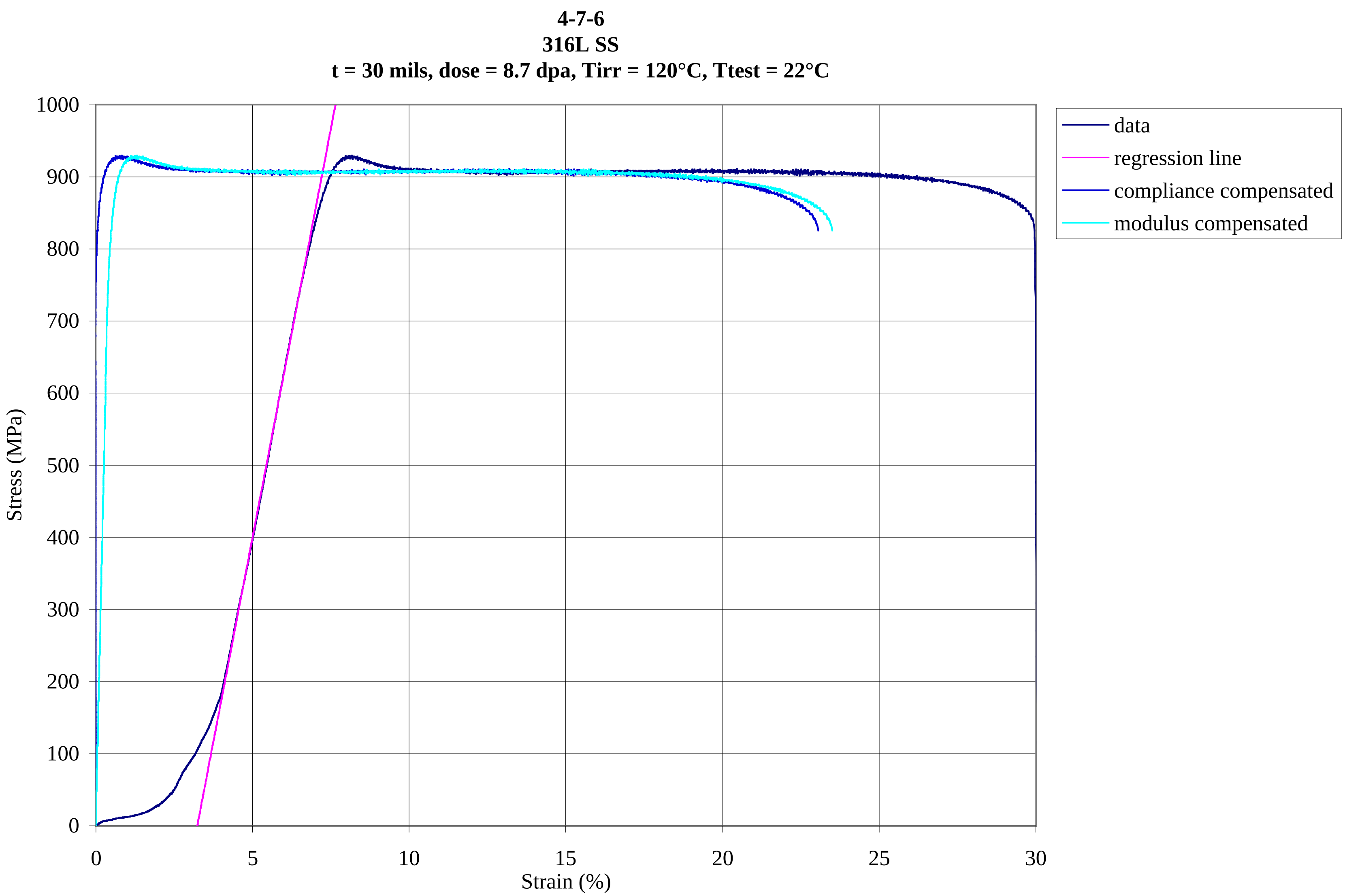

Figure A1-3 -- Tensile traces for specimen 4-7-6 (316L SS).

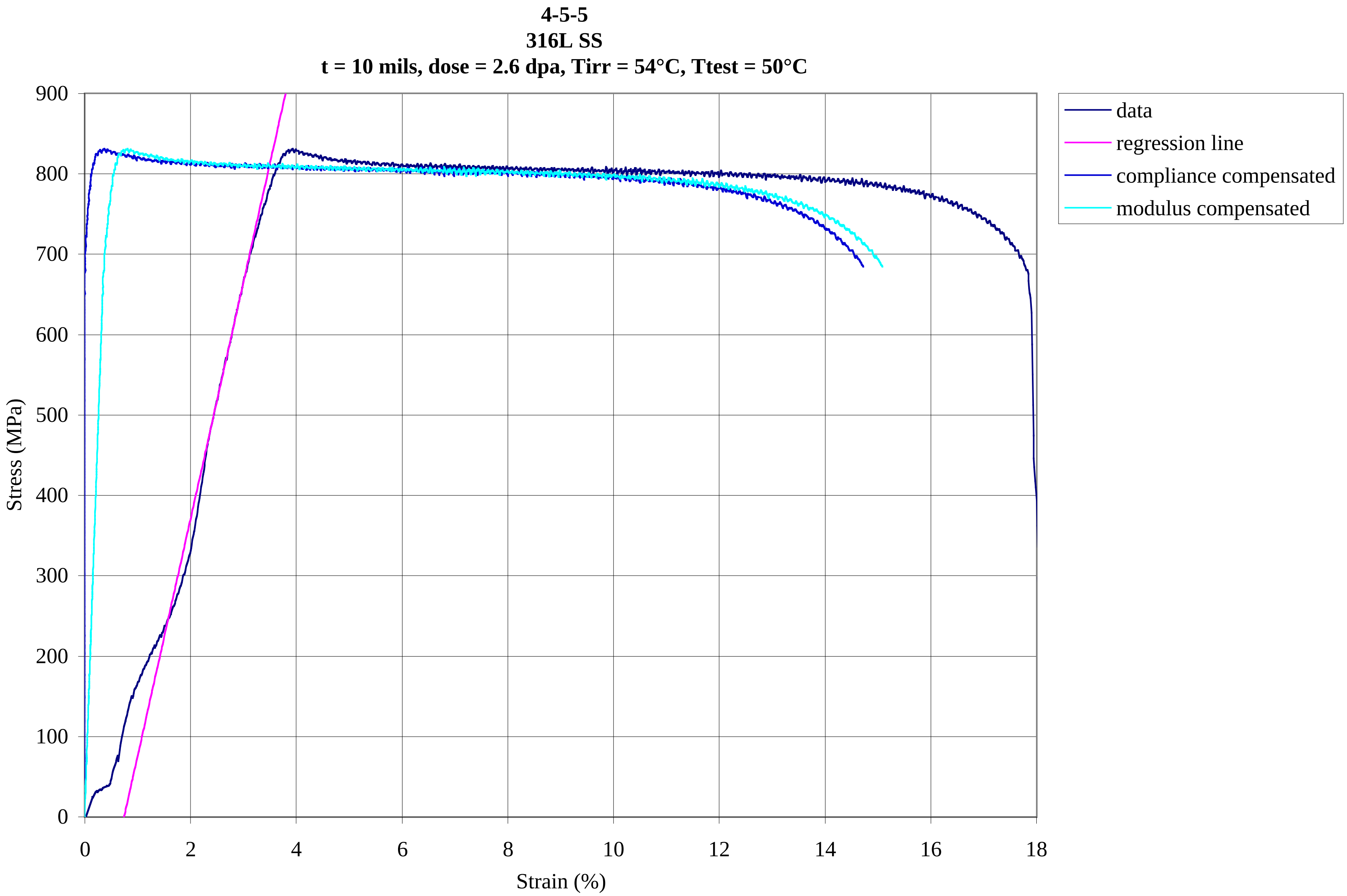

Figure A1-4 -- Tensile traces for specimen 4-5-5 (316L SS).

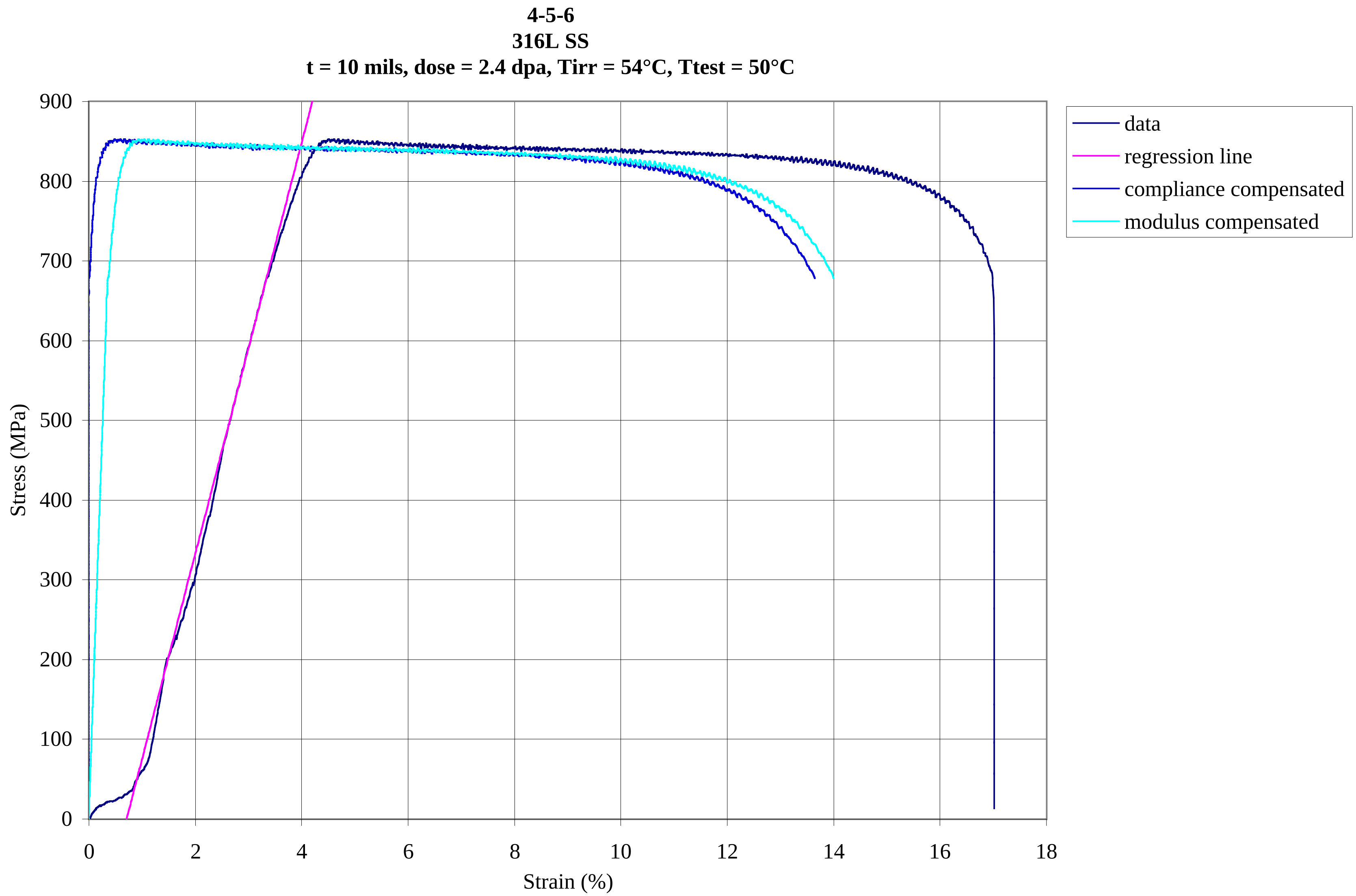

Figure A1-5 -- Tensile traces for specimen 4-5-6 (316L SS).

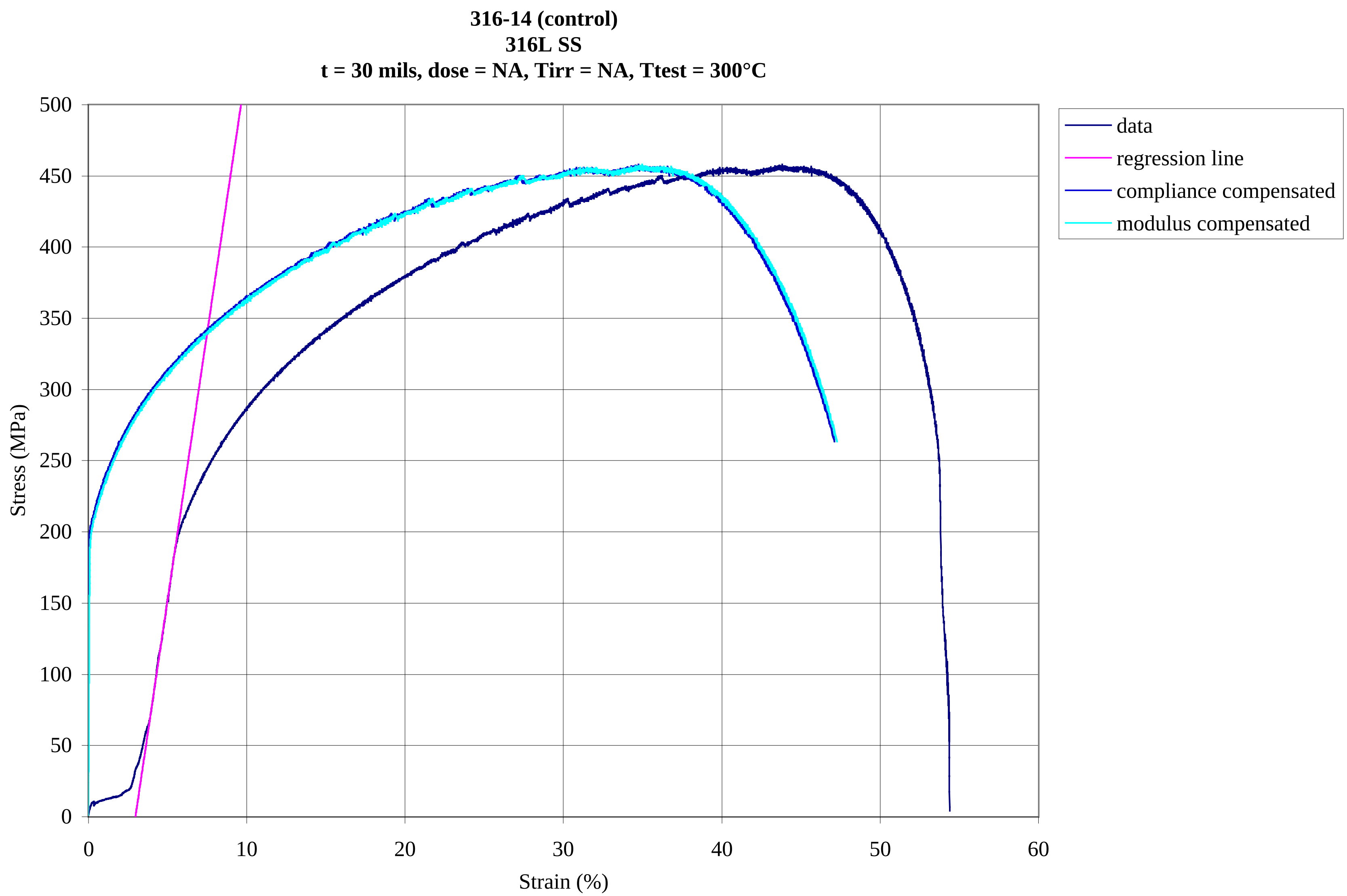

Figure A1-6 -- Tensile traces for specimen 316-14 (316L SS).

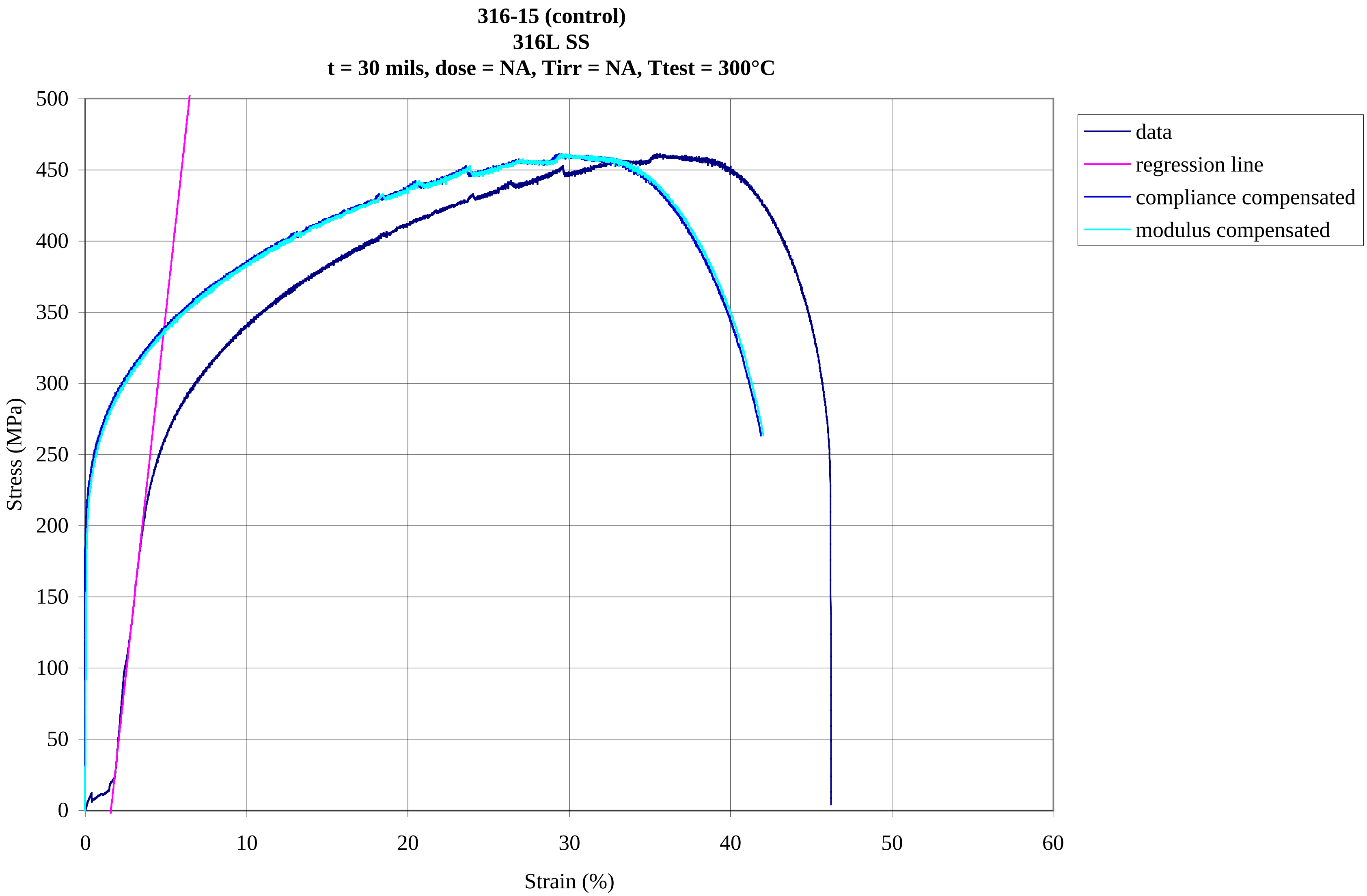

Figure A1-7 -- Tensile traces for specimen 316-15 (316L SS).

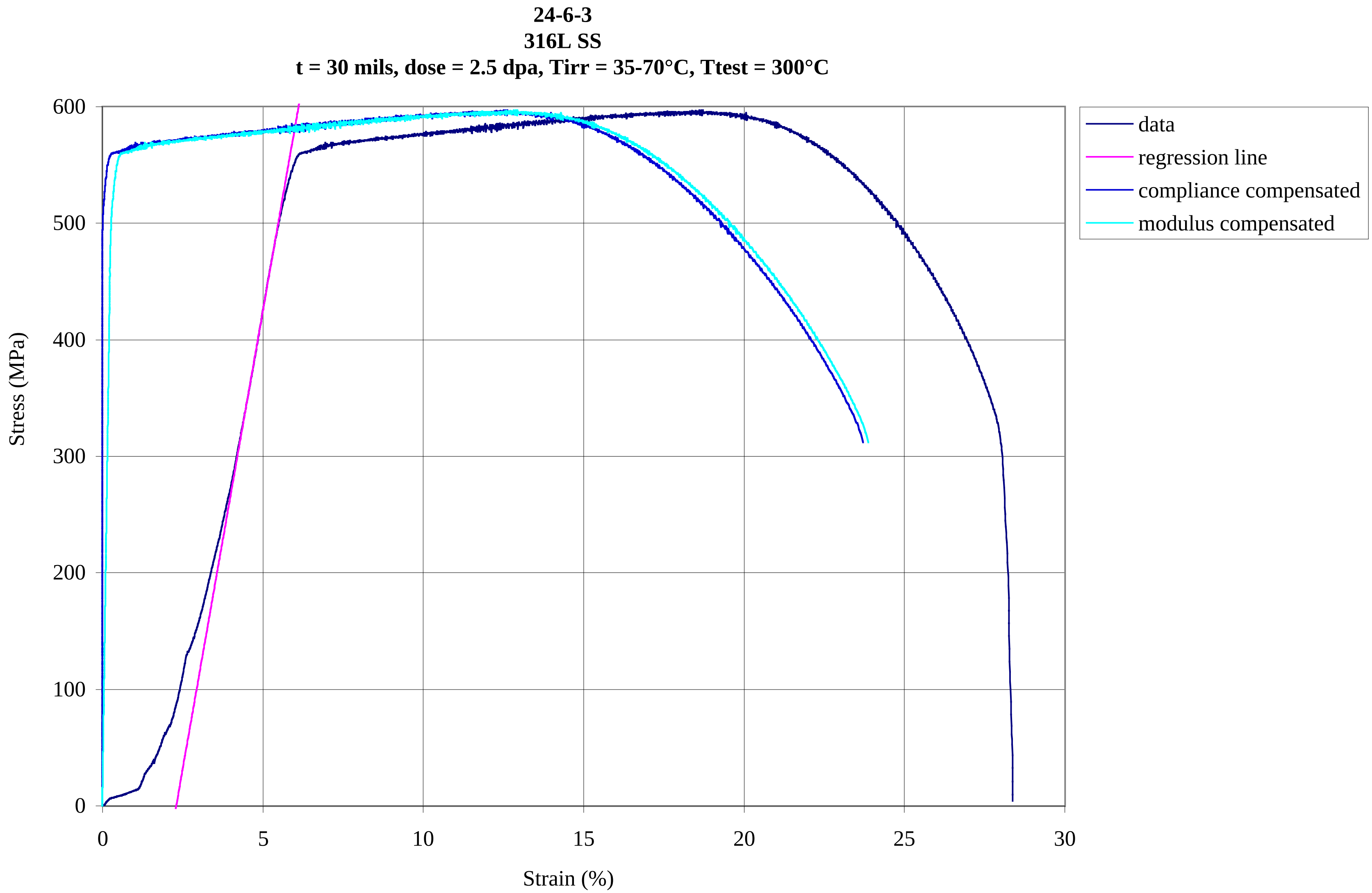

Figure A1-8 -- Tensile traces for specimen 24-6-3 (316L SS).

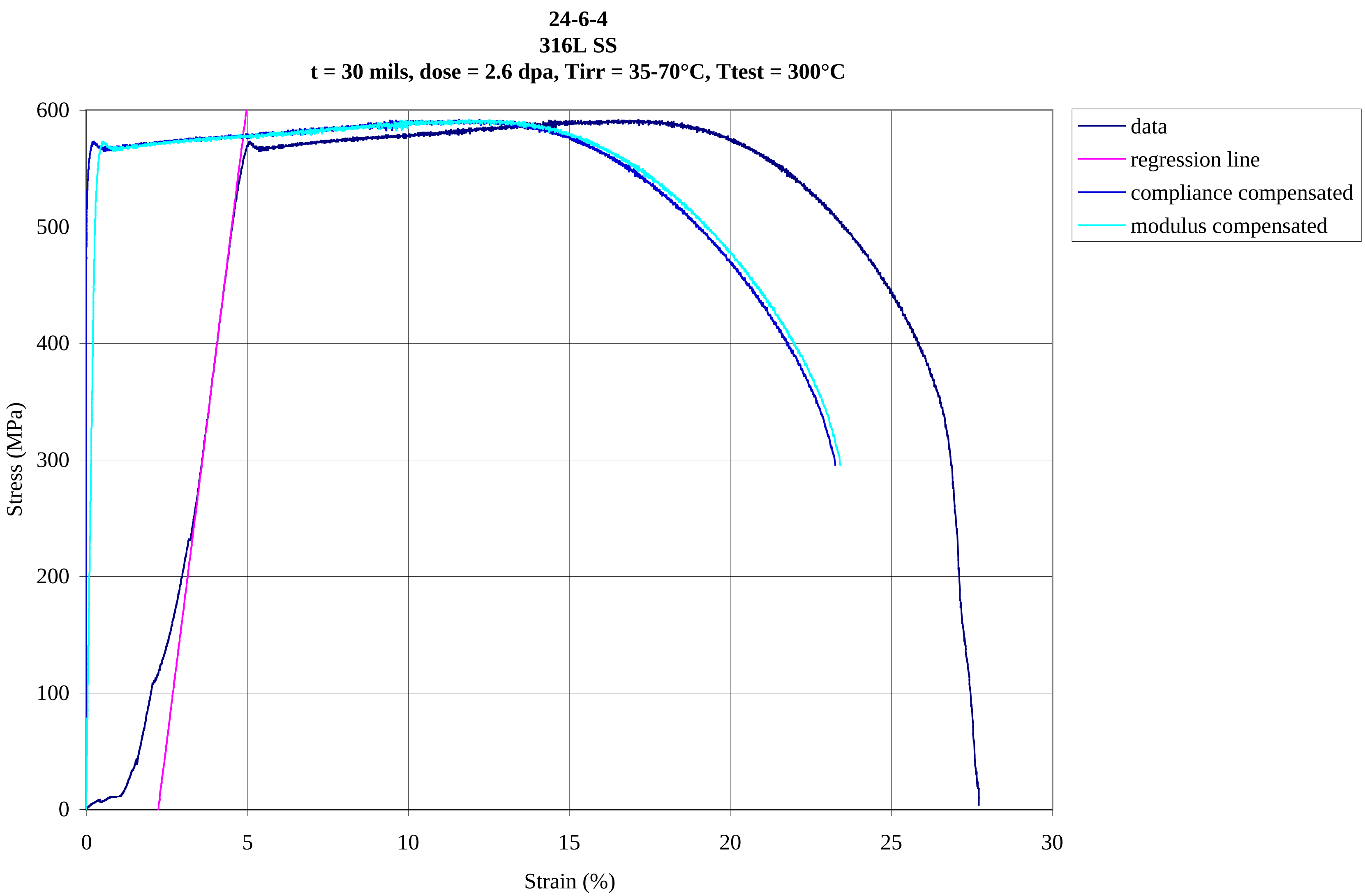

Figure A1-9 -- Tensile traces for specimen 24-6-4 (316L SS).

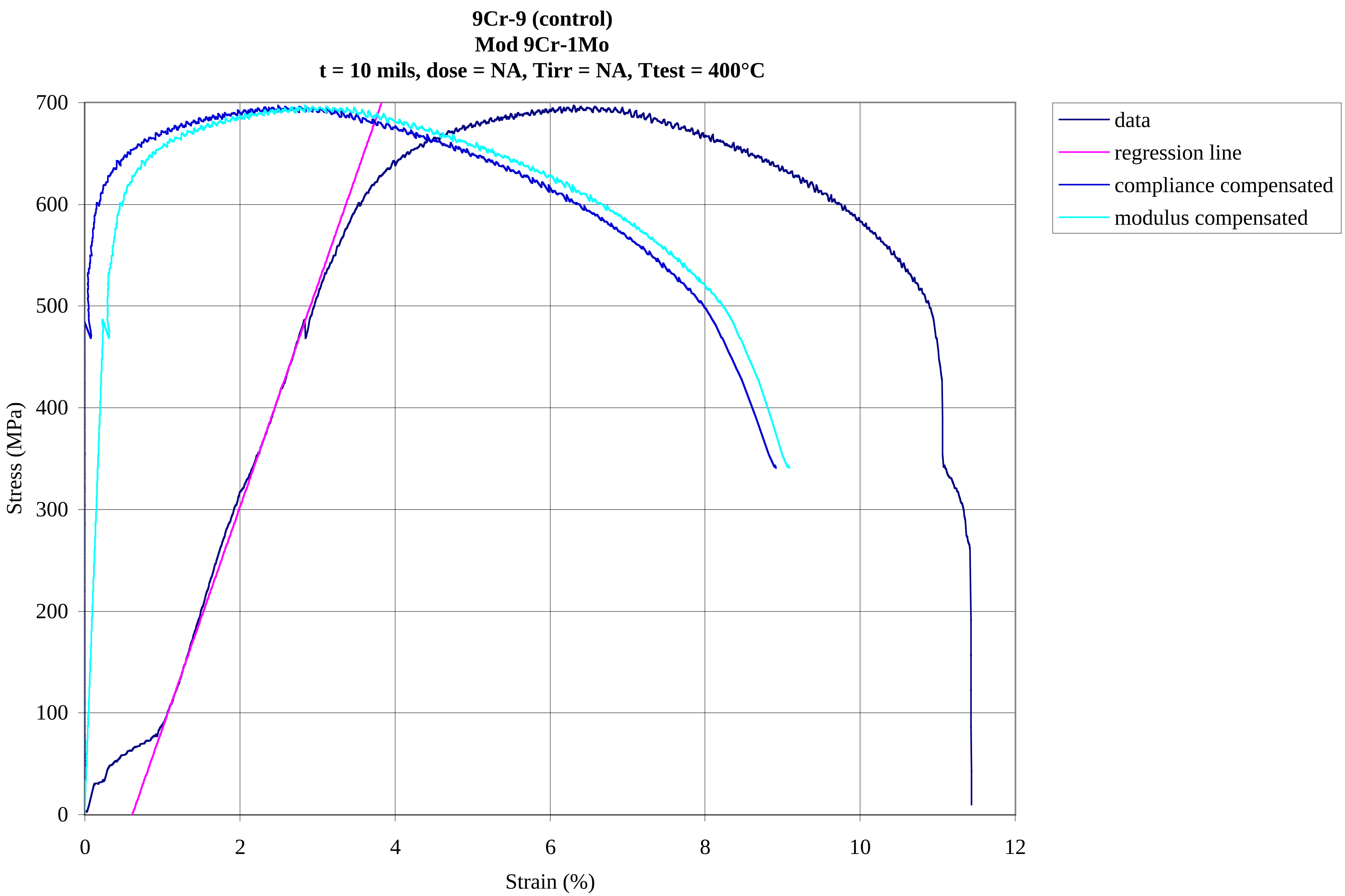

Figure A1-10 -- Tensile traces for specimen 9Cr-9 (Mod 9Cr-1Mo).

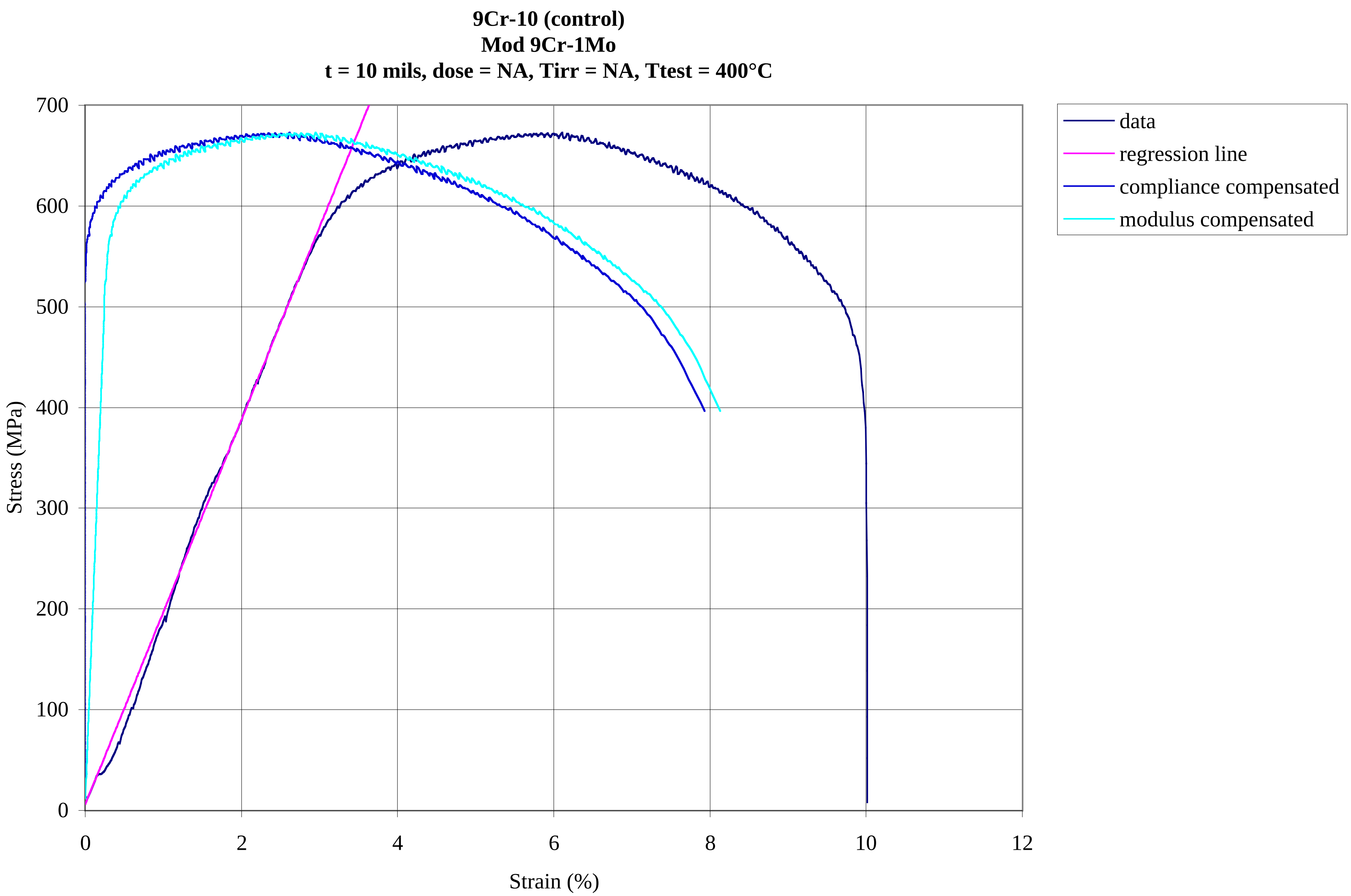

Figure A1-11 -- Tensile traces for specimen 9Cr-10 (Mod 9Cr-1Mo).

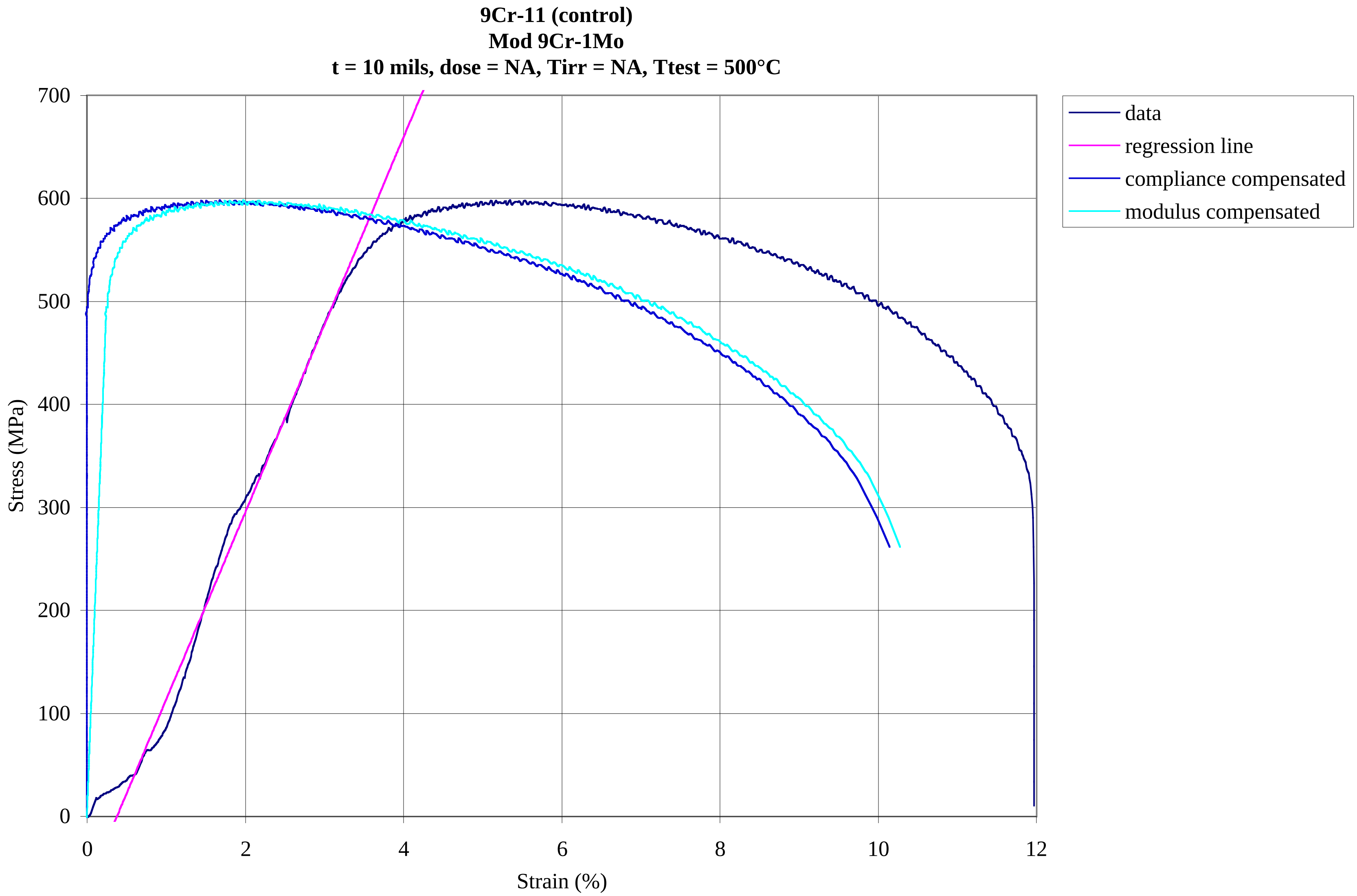

Figure A1-12 -- Tensile traces for specimen 9Cr-11 (Mod 9Cr-1Mo).

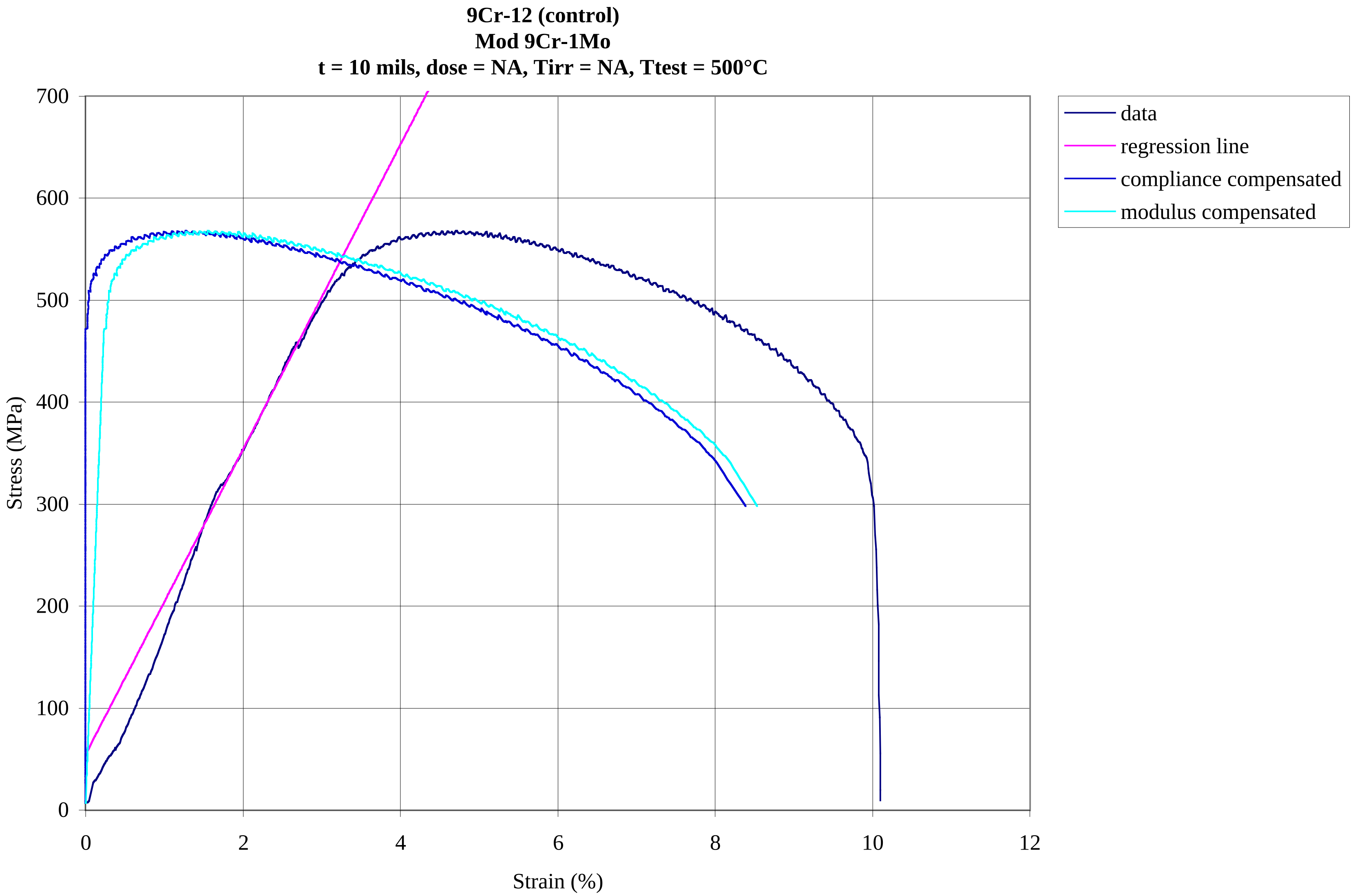

Figure A1-13 -- Tensile traces for specimen 9Cr-12 (Mod 9Cr-1Mo).

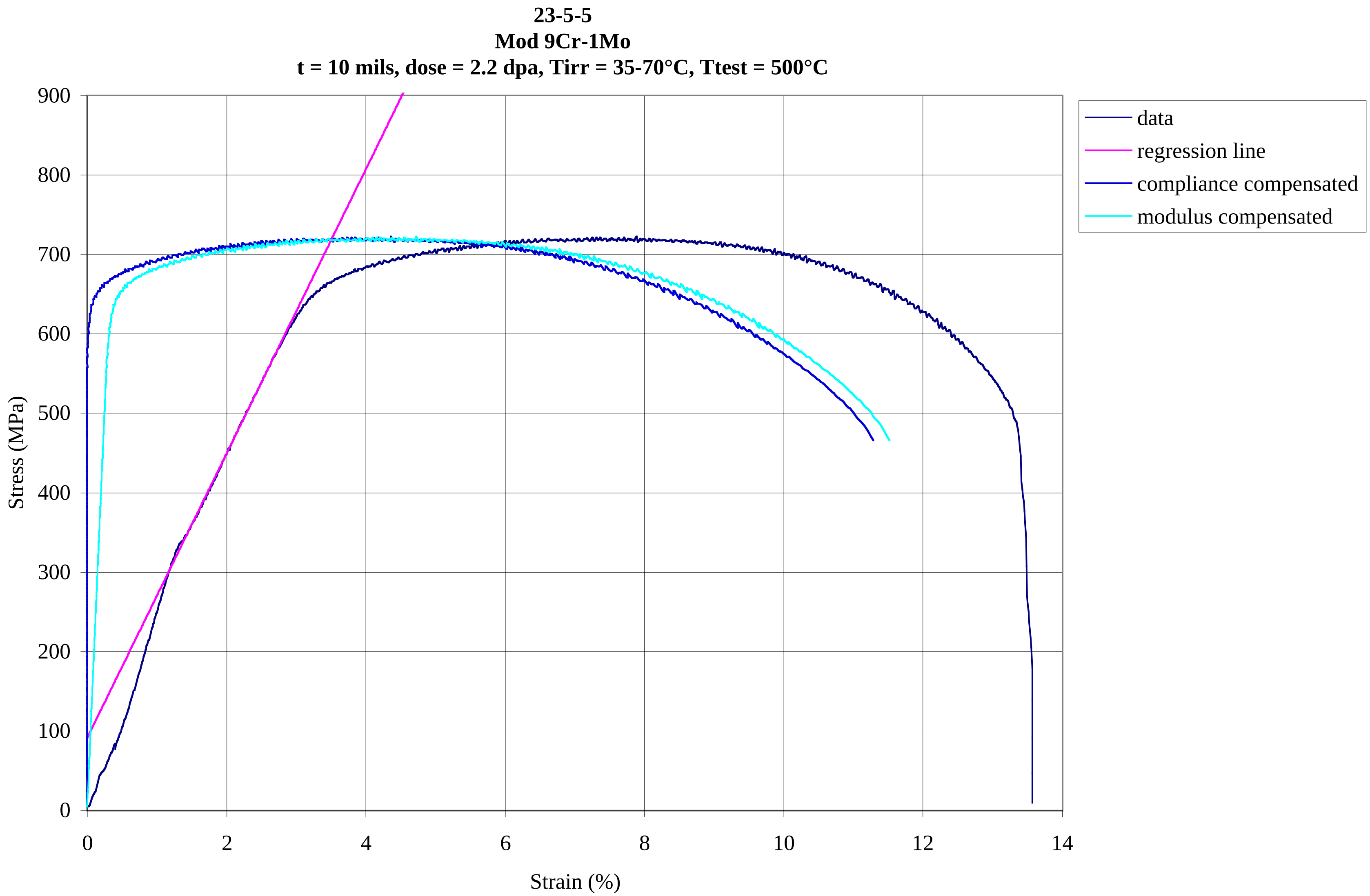

Figure A1-14 -- Tensile traces for specimen 23-5-5 (Mod 9Cr-1Mo).

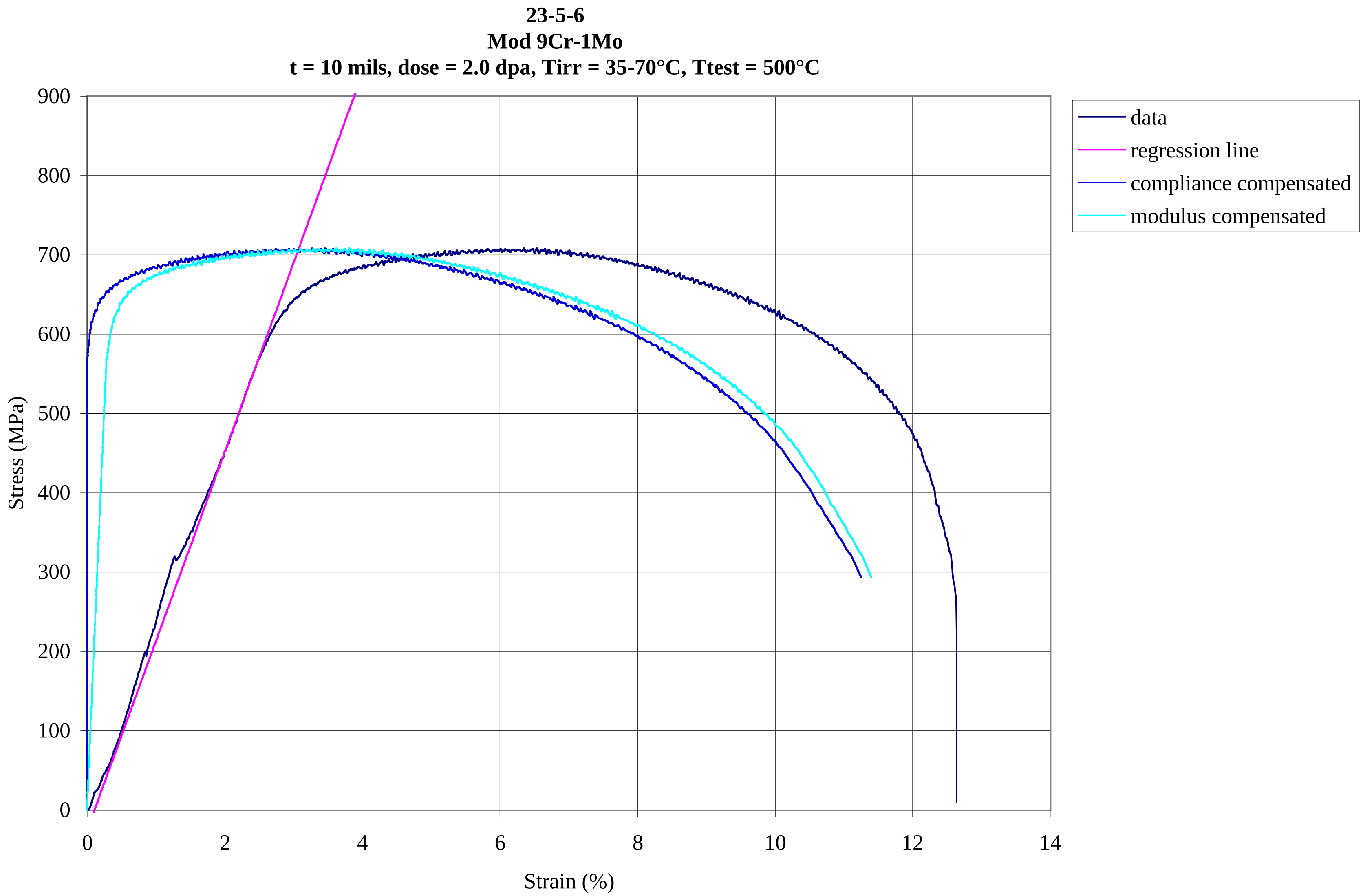

Figure A1-15 -- Tensile traces for specimen 23-5-6 (Mod 9Cr-1Mo).

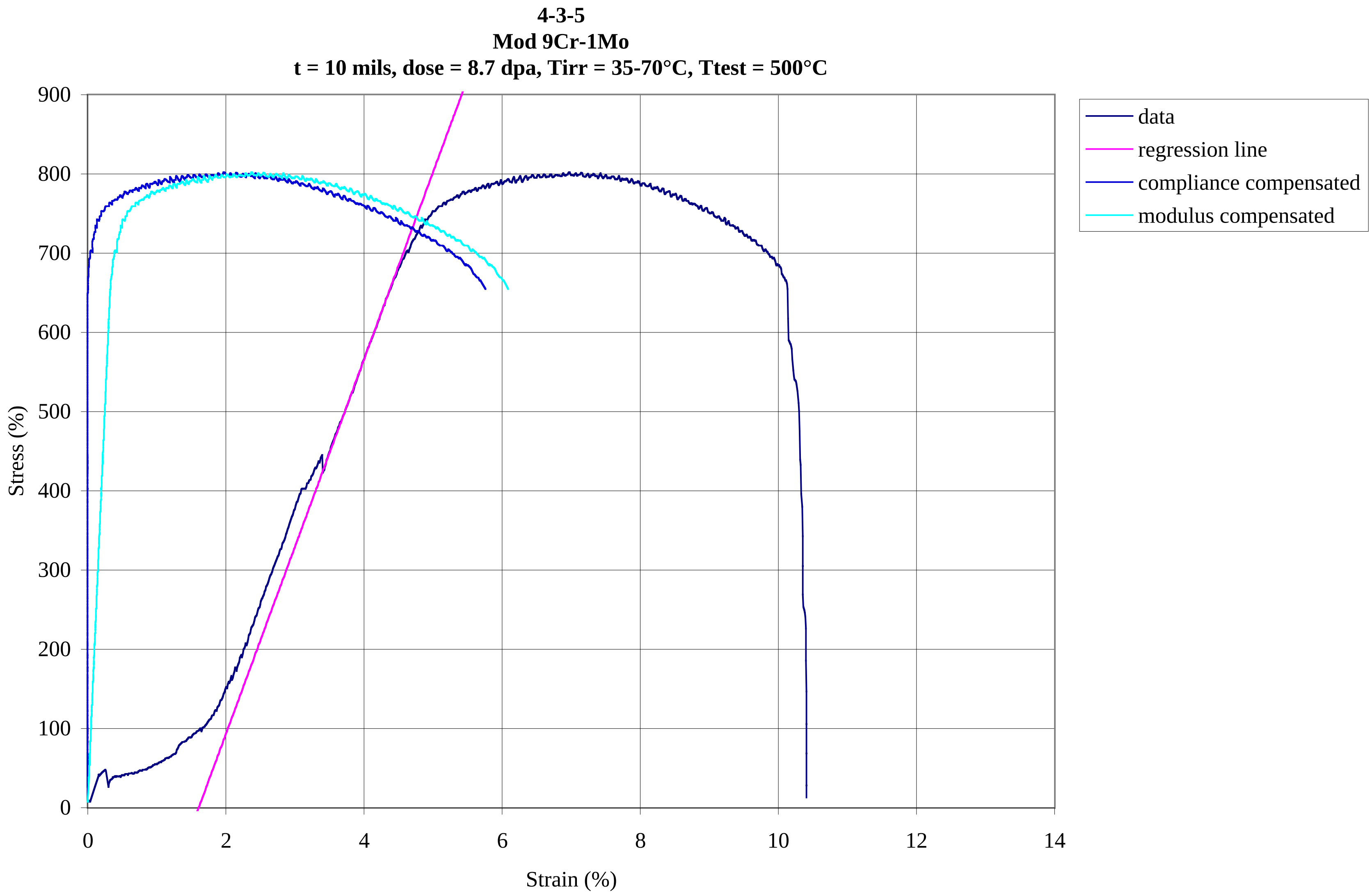

Figure A1-16 -- Tensile traces for specimen 4-3-5 (Mod 9Cr-1Mo).

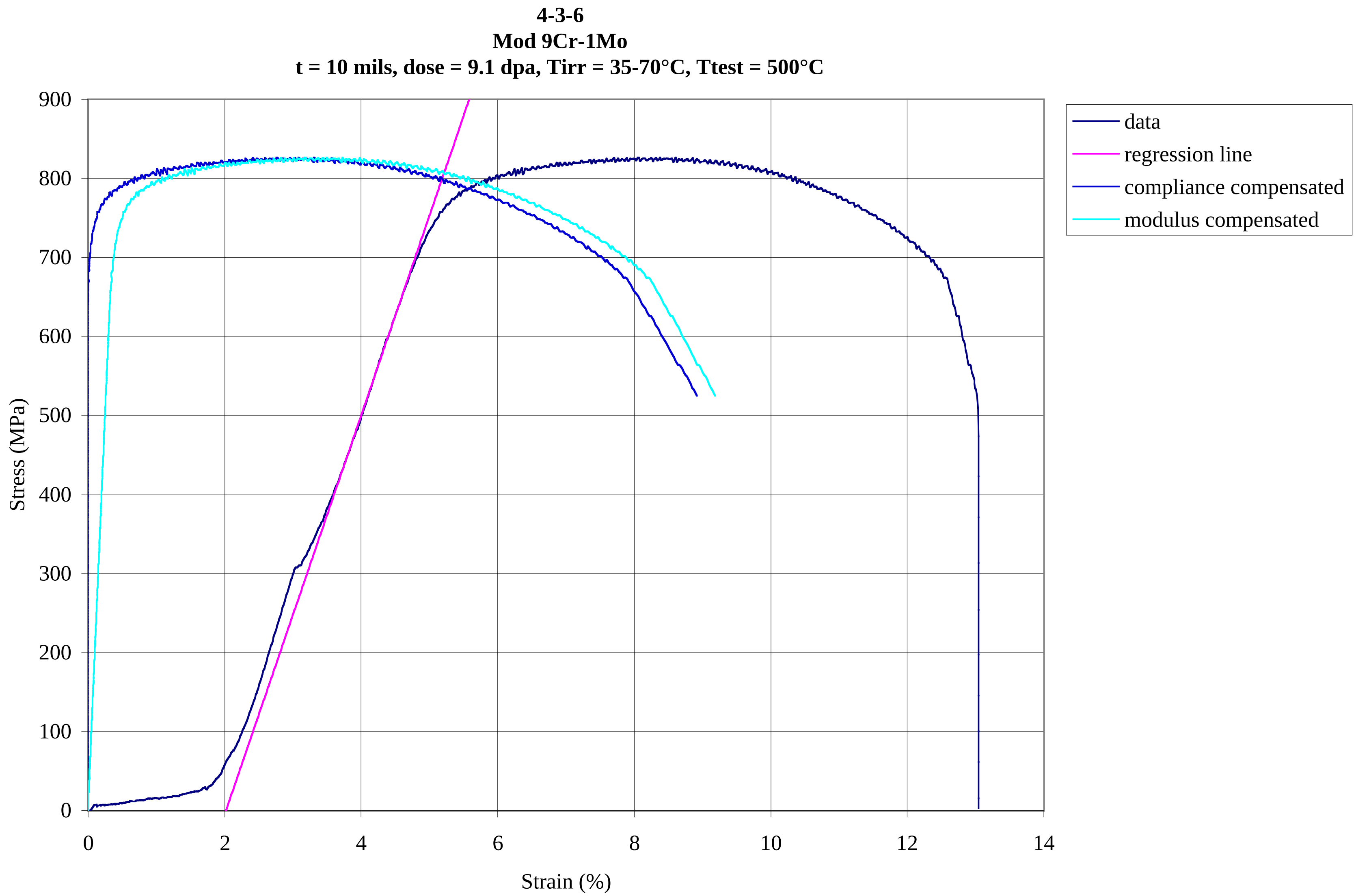

Figure A1-17 -- Tensile traces for specimen 4-3-6 (Mod 9Cr-1Mo).

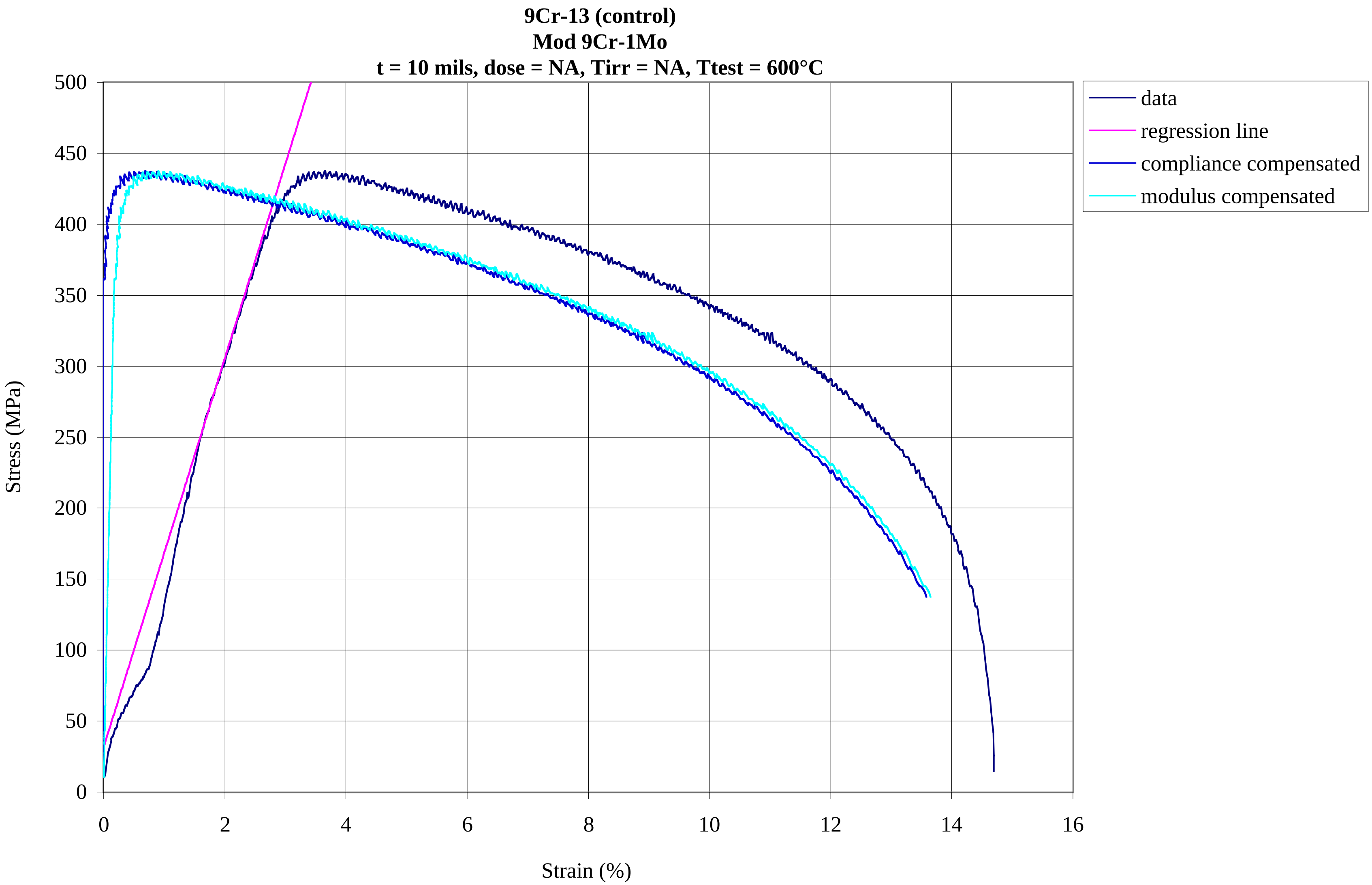

Figure A1-18 -- Tensile traces for specimen 9Cr-13 (Mod 9Cr-1Mo).

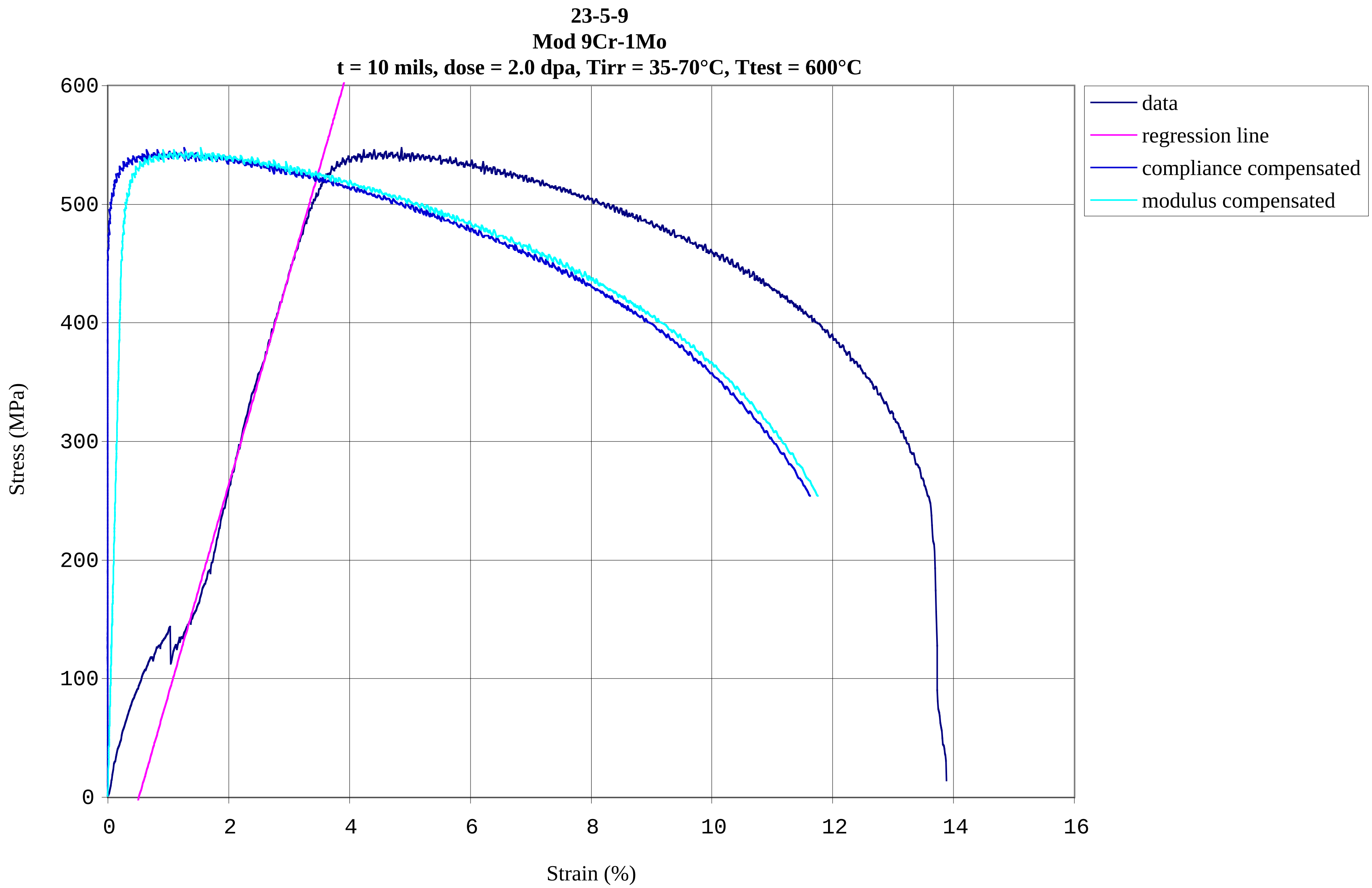

Figure A1-19 -- Tensile traces for specimen 23-5-9 (Mod 9Cr-1Mo).

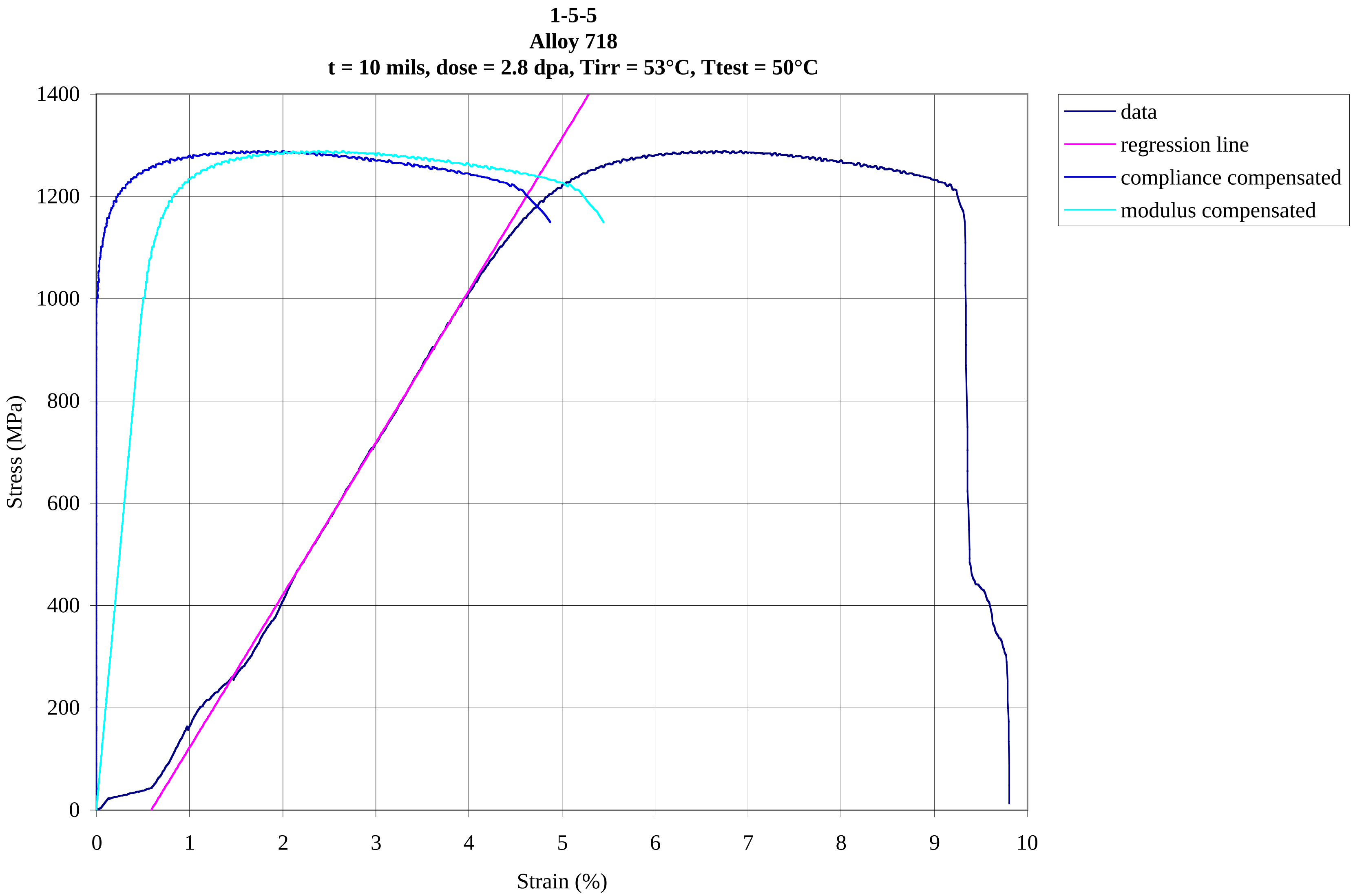

Figure A1-20 -- Tensile traces for specimen 1-5-5 (Alloy 718).

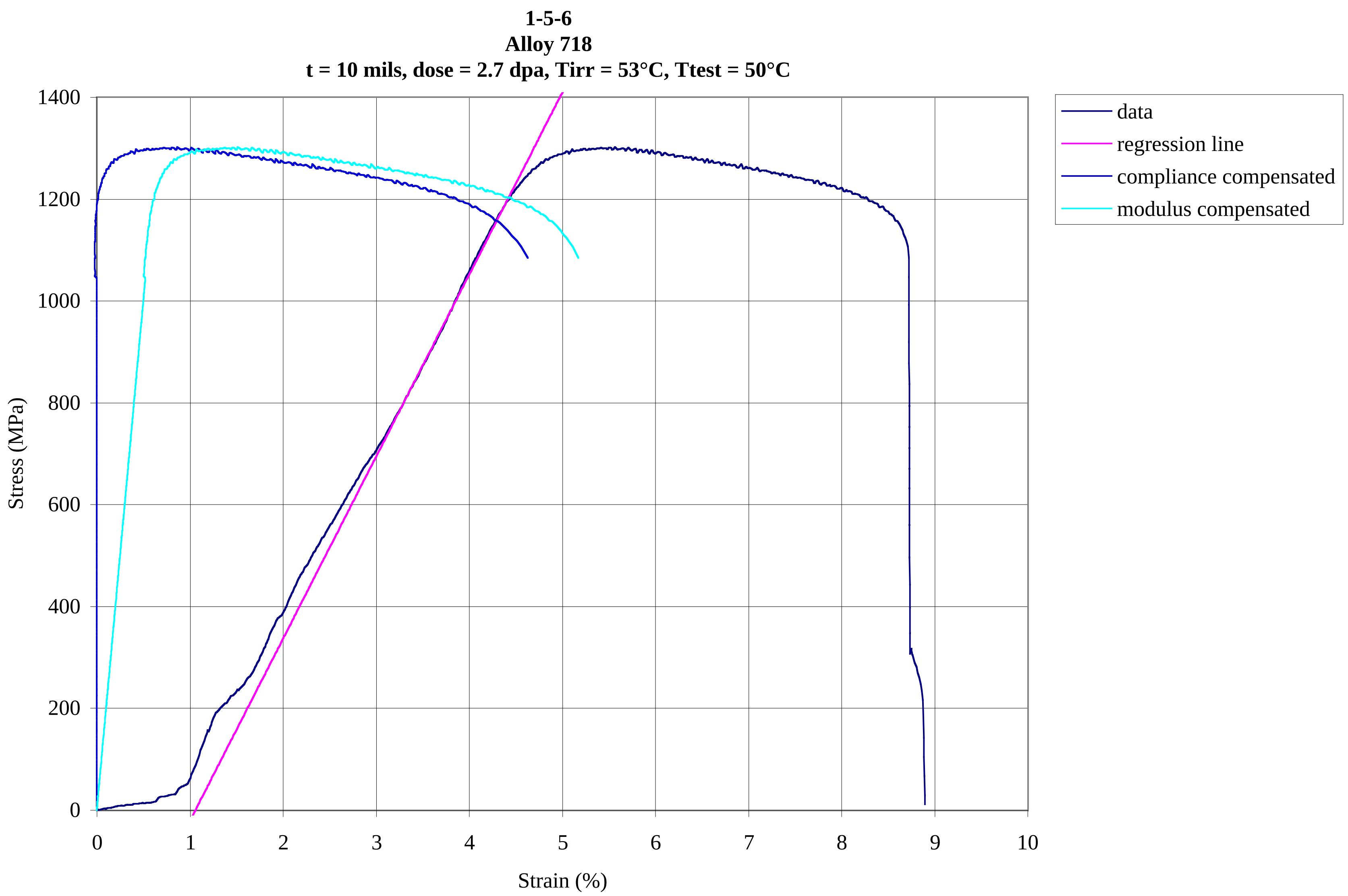

Figure A1-21 -- Tensile traces for specimen 1-5-6 (Alloy 718).

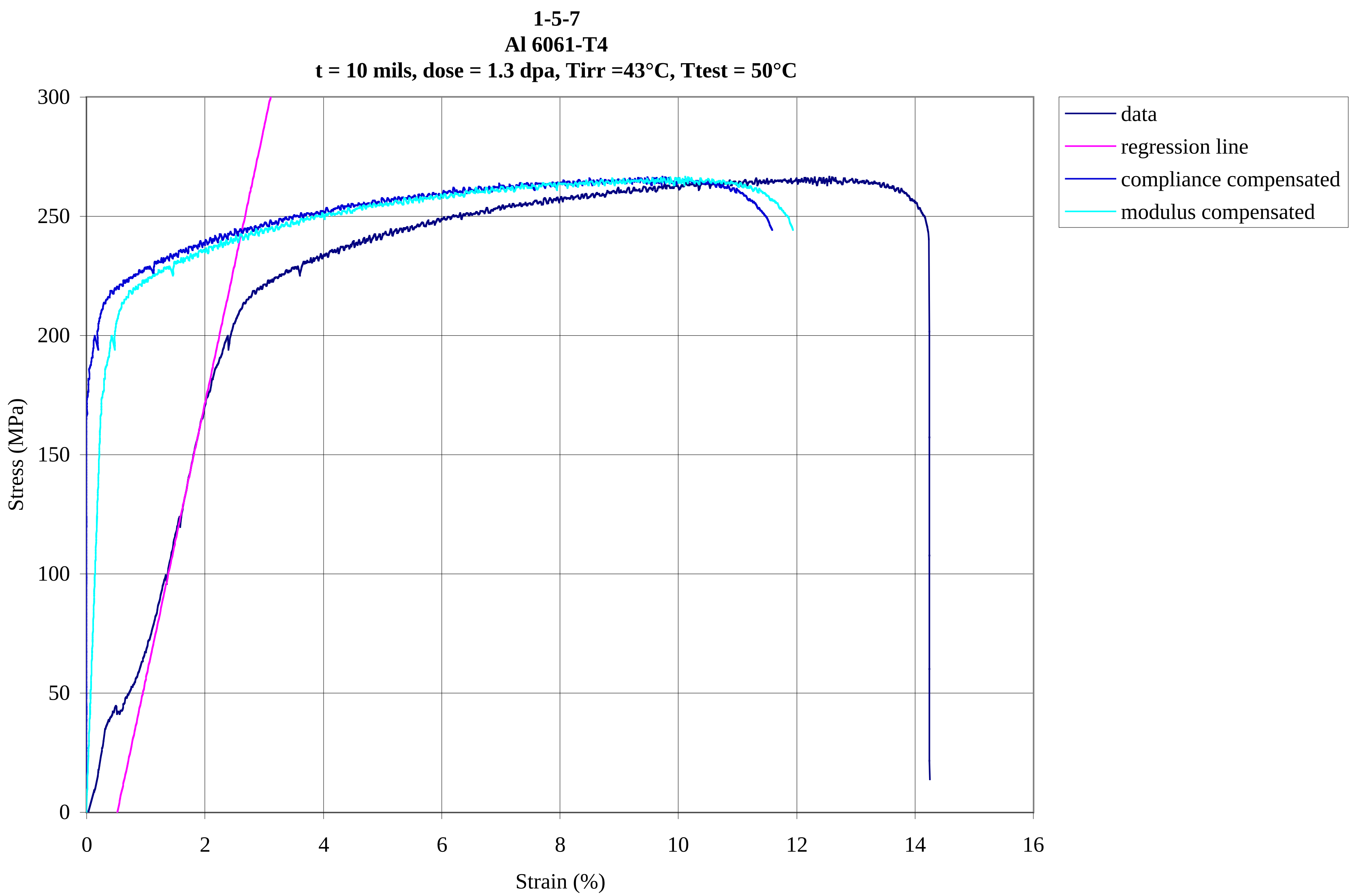

Figure A1-22 -- Tensile traces for specimen 1-5-7 (Al 6061-T4).

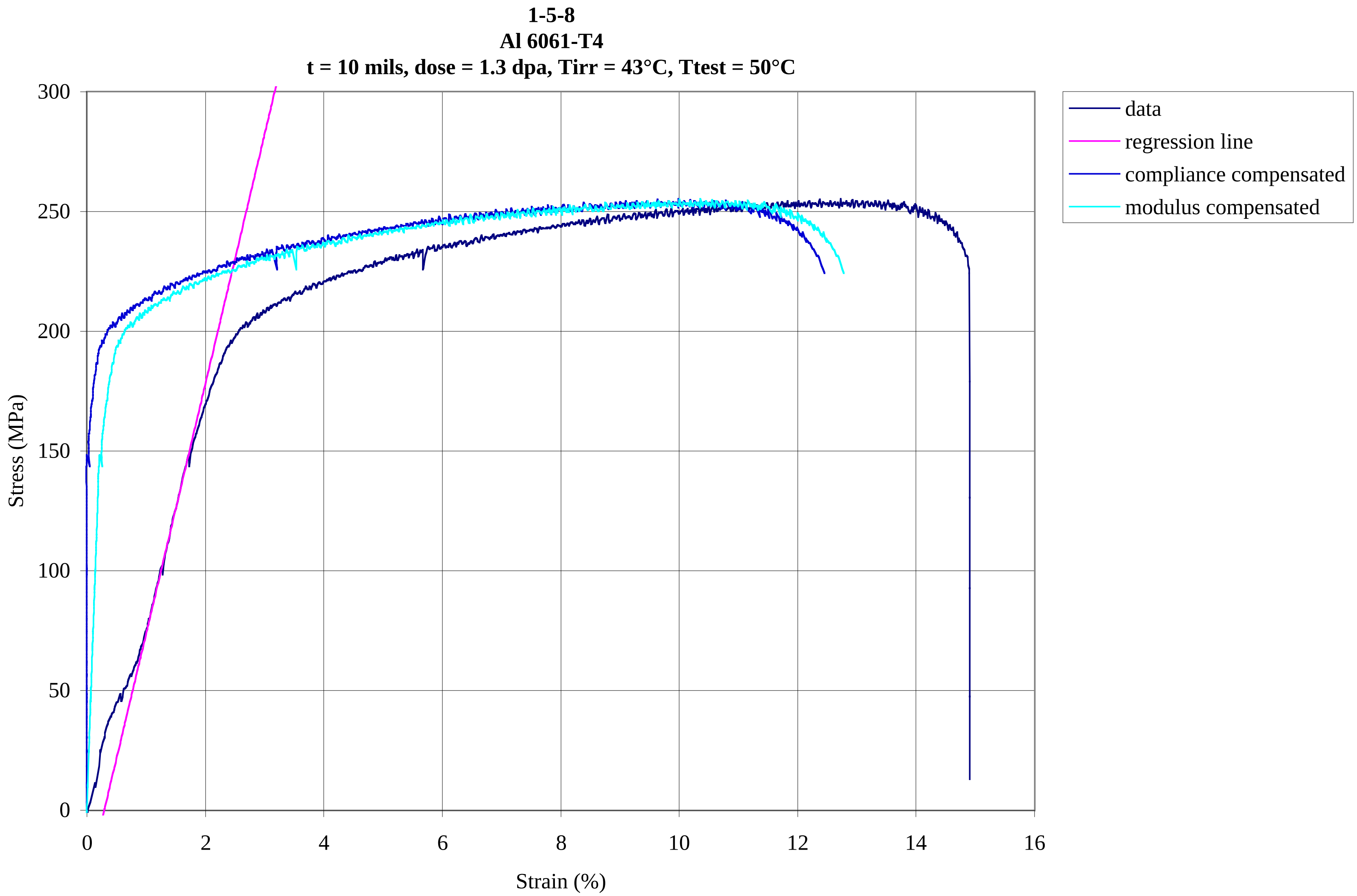

Figure A1-23 -- Tensile traces for specimen 1-5-8 (Al 6061-T4).

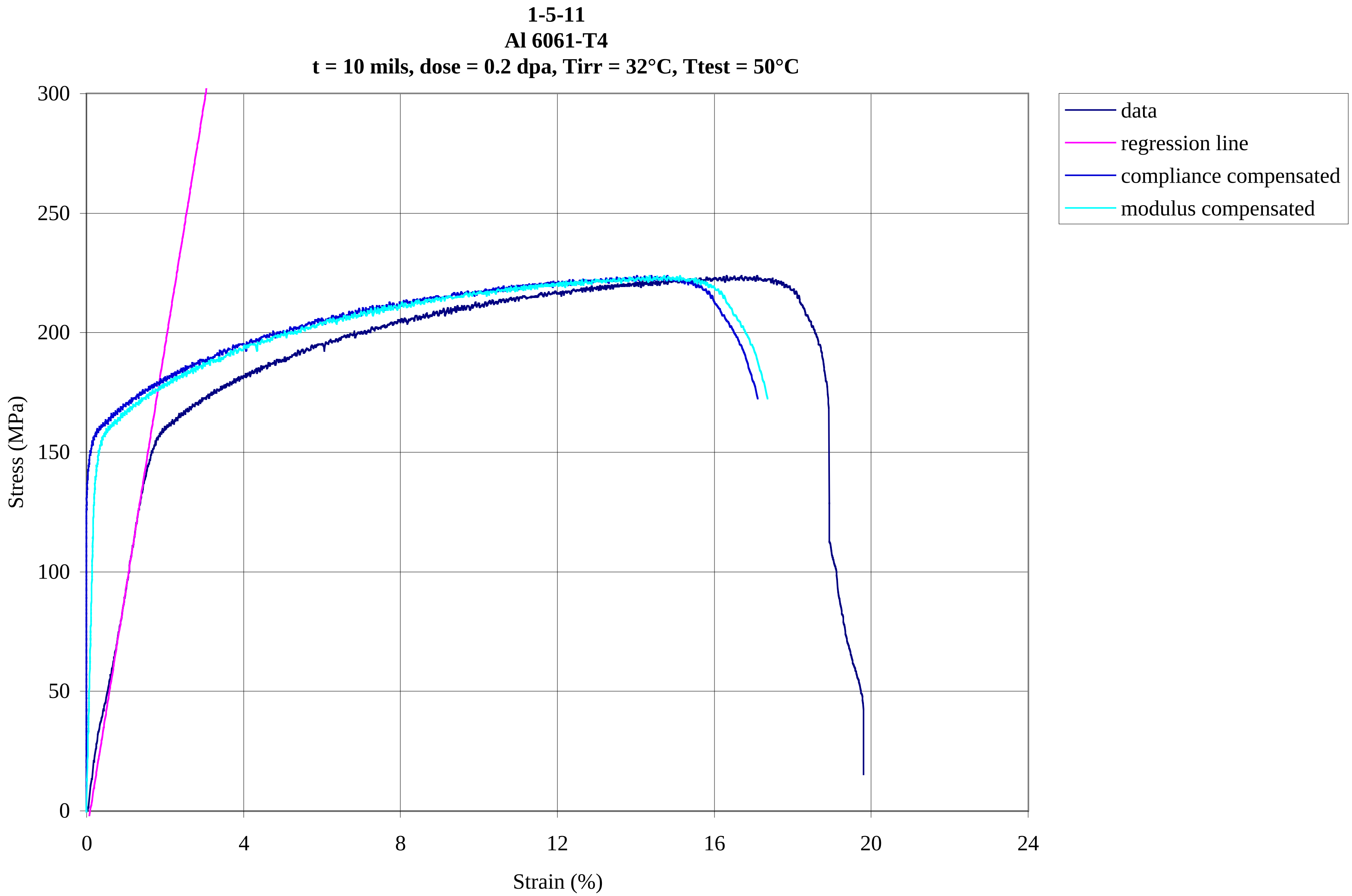

Figure A1-24 -- Tensile traces for specimen 1-5-11 (Al 6061-T4).

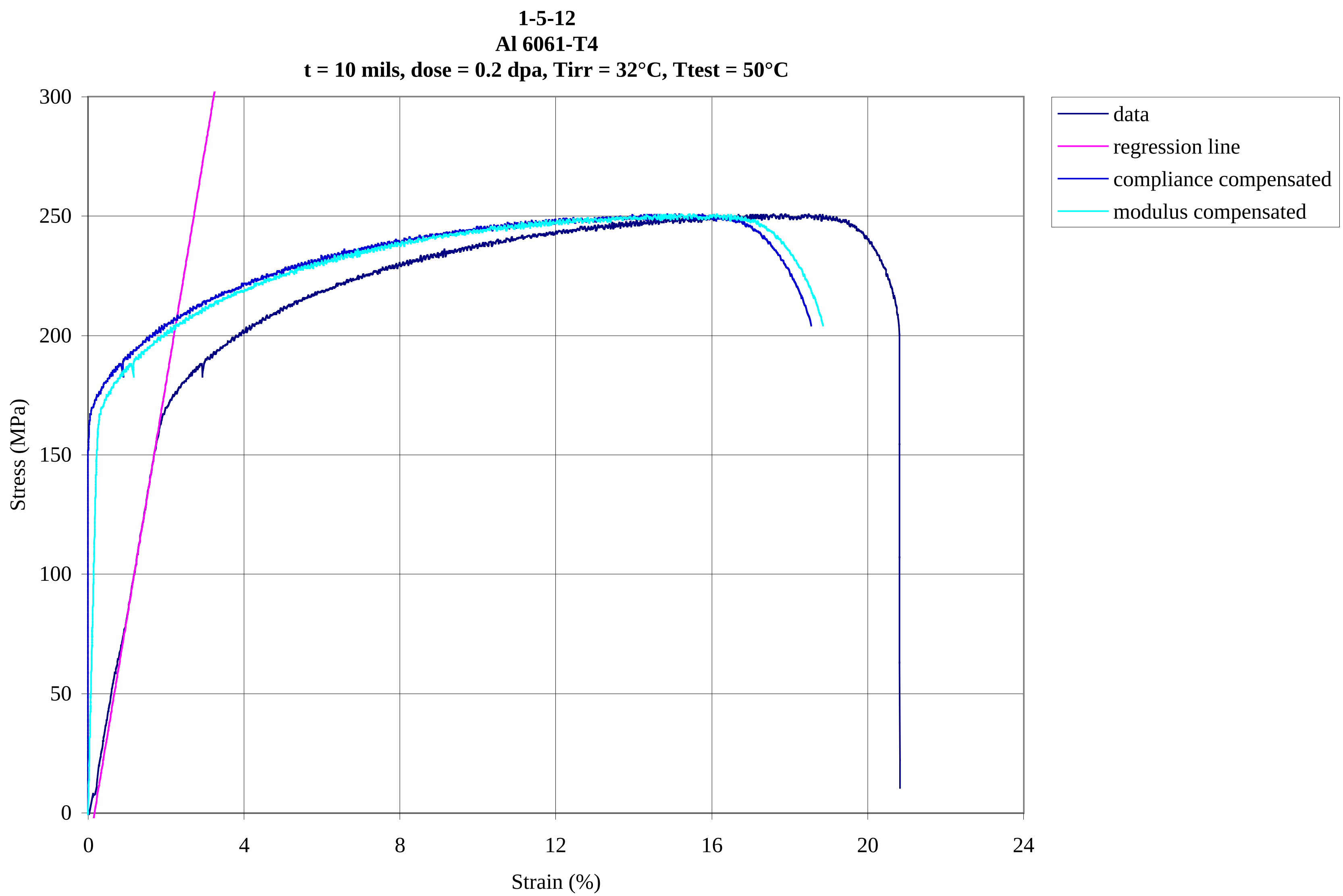

Figure A1-25 -- Tensile traces for specimen 1-5-12 (Al 6061-T4).